ALASKA'S SHRINKING GLACIERS:
INTEGRATED GLACIOLOGICAL RESEARCH FOR HYDROLOGICAL, ECOLOGICAL, AND ENVIRONMENTAL EDUCATION APPLICATIONS

By

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Abstract

As air temperatures in Alaska are rising, glacier melt is accelerating and affecting hydrological resources and downstream ecosystem function. The extent to which glacier loss may change hydrological regimes in coastal climates, and how that may impact nearshore marine conditions, is uncertain. Moreover, from a social-ecological standpoint, many citizens today are disconnected from these types of environmental changes, in part due to isolation from visible climate change impacts. This dissertation addresses the dual need for examining recent Alaska glacier changes and resulting hydrological and marine impacts, and for exploring education strategies that leverage glacier changes for environmental identity development. In Chapter One, I present a conceptual framework that links the physical and social sciences research herein as equal components of a social-ecological system. In Chapter Two, I use a glacio-hydrological model to uncover that coastal glaciers of the Juneau Icefield have yet to pass 'peak water' delivery. I also find that between 1980 to 2016, glacier ice melt increased annually (+10%, $p = 0.14$) and in spring (+16%, $p = 0.05$), leading to changing freshwater composition. In Chapter Three, I compare modeled Mendenhall River discharge to nearshore oceanographic measurements, finding that salinity and density in the upper 15 m are strongly glacially-influenced (10 to 30 PSU and 1010 to 1023 kg m^{-3}), and that glacier runoff exerts a stronger control ($r^2 = 0.66$) than total runoff. Large, significant trends are also detected for 1997 to 2016 August modeled glacier runoff ($p = 0.02$, +15%) and observed salinity ($p = 0.01$, -3.2 PSU), linking these phenomena and revealing ongoing changes. Finally, in Chapter Four, I analyze social science data from youth participants in a science outreach program in a climate-impacted glacier landscape. I find that better understanding ecosystem linkages and seeing the scale of glacier loss first-hand promote environmental identity development by building relatedness and pro-environmental motivation. Together, the glaciological and environmental education research herein provides diverse perspectives on improving both scientific and citizen understanding of glacier mass loss in a changing climate.

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Chapter 1: Advancing glaciology through lessons from ecology and resilience theory: A framework for integrating glaciology and environmental education research

1.1 Glacier mass loss in a changing climate

From a glaciologist's perspective, the glaciers of Alaska, USA, and Northwestern Canada – hereafter called Alaska glaciers for brevity – are a natural laboratory. Covering more than 87,000 km^2, an area greater than the five smallest US states combined, these glaciers are shedding mass at one of the highest rates of any mountain glacier system globally [*Gardner et al.*, 2013]. In their study, *Larsen et al.* [2015] calculated for all Alaska glaciers a loss of -75 $\pm$ 11 Gt $year^{-1}$ between 1994 to 2013, an amount equivalent to the annual loss of a 4.4 cm deep layer of water spread evenly over all of Alaska. Recent studies have also found that Alaska glaciers contributed an estimated 25% of 2003 to 2009 mean sea-level rise from mountain glacier systems (including the Greenland and Antarctic peripheries but excluding the ice sheets themselves) [*Arendt et al.*, 2013; *Gardner et al.*, 2013].

In much of the world including Alaska and Washington, glaciers reached a geologically recent peak in size during the Little Ice Age, a period of overall colder global temperatures and glacier advance between the 16th to mid-19th centuries [*Mann*, 2002]. This pattern was especially pronounced in the extratropical northern hemisphere [*Mann et al.*, 2009]. Evidence from lake sediment and tree-ring proxies place the end of the coldest period at approximately 1850 C.E. in Alaska [*Wiles et al.*, 1999; *Loso*, 2009]. After this, glaciers in Alaska began to recede [*Barclay et al.*, 2009]. This turning point also coincides closely with the late 19th-century onset of the steam engine-driven Industrial Revolution, a moment synchronous to when air trapped in polar ice began showing growing global concentrations of the greenhouse gases carbon dioxide and methane [*Crutzen*, 2002]. This has lead some geoscientists to coin the term 'Anthropocene' to mark the late 19th century as the beginning of a new geologic era dominated by human influence [*Crutzen and Stoermer*, 2000; *Crutzen*, 2002].

Today, Alaska's glaciers are continuing this trend of mass loss that began at the end of the Little Ice Age, with patterns of thinning and retreat that have long been recognized as strongly correlated with climate change [*Dyurgerov and Meier*, 2000; *Roe et al.*, 2017]. Evidence of climate change includes: increases in air temperature that are currently 1.0°C above pre-industrial levels, with increases in the Arctic at least two times as large [*Masson-Delmotte et al.*, 2018] due to a phenomenon dubbed Arctic amplification [*Screen and Simmonds*, 2010; *Serreze and Barry*, 2011; *Cohen et al.*, 2014]; changes in snow trends [*Liston and Hiemstra*, 2011; *Cohen et al.*, 2012], and changes in snow/rain partitioning [*McAfee et al.*, 2014]. Alaska glacier mass changes have been directly correlated with these climate variables [*Arendt et al.*, 2009; *Criscitiello et al.*, 2010], with evidence that losses are dominated by summer air temperatures [*Arendt et al.*, 2009; *Criscitiello et al.*, 2010; *O'Neel et al.*, 2014]. Moreover, a modeling investigation on maritime Arctic glaciers shows that a 1°C increase in air temperature can only be offset by a 50% increase in solid precipitation [*De Woul and Hock*, 2005], a change for which there is little evidence in projection studies. Rather, studies currently project a loss of up to 60% of Alaska glacier volume by 2100 under realistic emissions scenarios [*Radić et al.*, 2014], with considerable consequences for not only magnitudes but also timing of glacier runoff [*Radić and Hock*, 2014].

1.2 Glaciers as a hydrological resource

From a hydrological perspective, glaciers play a crucial role in the timing, volume, and biogeochemical signature of freshwater runoff along the Gulf of Alaska [*O'Neel et al.*, 2015]. Glaciers act as a frozen freshwater reservoir, with the ability to temporarily store water over diurnal, seasonal, and long-term (decadal to millennial) time scales [*Jansson et al.*, 2003]. Drainages containing even as little as 5% glacier cover exhibit modified flow patterns compared to their ice-free equivalents, by delayed peak runoff contemporaneous with peak temperatures in mid-summer and by a decrease in annual and monthly variability [*Fountain and Tangborn*, 1985]. Streamflow measurements downstream of glaciers with persistent negative net mass balance display a pattern characterized initially by increased discharge due to higher rates of mass loss up until a maximum (often referred to as 'peak water' [*Gleick and Palaniappan*, 2010]), followed by decreased discharge due to shrinking glacier area and volume [*Jansson et al.*, 2003]. Indeed, one of the most sought-after pieces of information for those studying watershed or regional hydrology is in knowing whether a glacierized basin or region is in an overall state of increasing or decreasing flow. The answer to this is linked to several factors. *Moore et al.* [2009] for example identified geographic variations in runoff trends for Western North American glacierized basins, whereby basins with larger glaciers in the north still show increasing runoff, while basins with smaller glaciers further south have already passed the point of peak water. On the other hand, *Carnahan et al.* [2018] found in their glacier flow modeling study that glacier dynamics (characterized by response times) and landscape evolution (i.e. vegetation succession after deglaciation) had a roughly equal impact on basin runoff in response to climate.

Glacier runoff, whether from melted glacier ice or from terrestrial water that has passed through a glacier system, also carries a unique biogeochemical signature with implications for the function of downstream ecosystems. For example, glacier runoff has been found to control fluxes of limiting nutrients crucial for primary productivity in riverine and marine environments. A study on Juneau Icefield streams found that glaciers serve as an important source of phosphorus and nitrogen [*Hood and Scott*, 2008], while nearby rivers such as the Copper have proven a critical source of iron to the Gulf of Alaska [*Crusius et al.*, 2011]. Glacier meltwater also serves as a major source of bioavailable organic carbon [*Hood et al.*, 2009], which readily assimilates into the downstream marine food web [*Fellman et al.*, 2015]. Moreover, glacier runoff possesses physical properties that are distinct from other terrestrial water sources. In comparing several Juneau Icefield watersheds, previous studies have found that both summer stream turbidity and water temperature could be predicted by the percentage of glacier cover within the basin [*Hood and Berner*, 2009; *Fellman et al.*, 2014].

Zooming out to the regional scale, runoff sourced from the 87,000 km^2 of glacier ice (~18% of the Gulf of Alaska watershed) [*Kienholz et al.*, 2015] makes up nearly half (38 to 47%) of the annual freshwater input into the Gulf of Alaska, including 7 to 10% that is attributed to glacier volume loss in different studies [*Neal et al.*, 2010; *Hill et al.*, 2015; *Beamer et al.*, 2016]. This input acts as a principal driver of the Alaska Coastal Current, a nearshore current that establishes salinity patterns and delivers critical nutrients along the entire Gulf of Alaska coast [*Royer*, 1981; *Weingartner et al.*, 2005; *Neal et al.*, 2010].

1.3 Glacier impacts on downstream ecosystems

From an ecological perspective, glaciers are a key feature controlling biogeophysical conditions in aquatic and terrestrial ecosystems along the Gulf of Alaska. Given steep topography that rises abruptly from sea level to >5000 m a.s.l., and a maritime climate that delivers 2 to 8 m w.e. of snow and rain per year [*Daly et al.*, 2008], the Gulf of Alaska watershed is characterized by both extensive glacier cover and extreme volumes of freshwater runoff. Unlike other major watersheds in North America that are dominated by large rivers, ~80% of Gulf of Alaska runoff is delivered from the steep topography to the coast via short (~10 km average), small drainages [*Neal et al.*, 2010; *O'Neel et al.*, 2015]. Glacier termini also often lie below treeline, placing glacier ice directly adjacent to the mixed forest of the northern Pacific temperate rainforest. Together, these unique qualities set up a tight coupling between ice and snow melt from alpine terrain and terrestrial and nearshore marine ecosystems downstream.

Given this strong linkage, glacier runoff (freshwater from ice melt, snow melt, or rain from the glacier surface) has numerous ecological influences. First, it possesses physical attributes like temperature and turbidity that are distinct from other terrestrial water sources [*Hood and Berner*, 2009]. Glacier runoff has also been found to influence fluxes of limiting nutrients such as phosphorus, nitrogen, and iron [*Hood et al.*, 2009; *Crusius et al.*, 2011] and bioavailable organic carbon [*Hood et al.*, 2009; *Fellman et al.*, 2015]. Even small drainages can yield high nutrient and sediment loading to the greater coastal oceans [*Destouni et al.*, 2008].

In glacier-influenced nearshore marine environments, glacier runoff also plays a role in biological productivity at all trophic levels, beginning with primary productivity, i.e. the production of organic compounds from carbon dioxide. From carbon stable isotope analysis, ancient glacier-sourced organic carbon has been traced through the proglacial riverine food web first by uptake into biofilm (bacterial aggregates that form on rocks and river bottoms) to macroinvertebrates to juvenile salmonids [*Fellman et al.*, 2015]. *Arimitsu et al.* [2016] found that phytoplankton abundance in several Alaska glacier fjords could be explained by physical gradients and nutrient availability resulting from the presence of glaciers, which influenced fjord ecosystem structure as far as 10km from shore. The same study also found that copepod and fish distribution were related to gradients in turbidity and temperature attributable to glacier freshwater input into the fjord, and that the distribution of seabirds was in turn explained by the availability of those prey species. Seals and whales have similarly been found to congregate around glacier fjord feeding hotspots, particularly where plankton and fish are entrained in freshwater upwelling at the glacier terminus [*Lydersen et al.*, 2014].

One family of species that is particularly important in coastal Alaska for cultural, subsistence, and economic reasons is Pacific salmon (*Oncorhynchus* spp.). These anadromous (i.e. both ocean- and freshwater-dwelling) species spend varying residence times in freshwater streams during their first months or years, and again when spawning at the end of life. For these species, stream temperature and geomorphology [*Lisi et al.*, 2013], clarity [*Milner and Bailey*, 1989], gravel-bottom sediment characteristics [*Lorenz and Filer*, 1989], and discharge amount and timing [*Dorava and Milner*, 2000; *Royer et al.*, 2001] are all key variables in both spawning ground selection and timing. These, as well as other factors such as flooding of low-elevation rearing grounds for juvenile pink salmon [*Lisi et al.*, 2013] and the extremely sharp thermal limits for adult sockeye salmon survival *Welch et al.* [1998], all have the potential to be impacted by changing glacier runoff in a changing climate.

1.4 Glaciers as an environmental education tool

Today in the U.S., although 97% of the scientific community who specialize in climate-related fields agree on both the occurrence and cause of climate change [*Doran and Zimmerman*, 2009; *Cook et al.*, 2016], belief among members of the public remains much less strong. Current studies show that approximately 9% of the general U.S. population continues to altogether disbelieve in the occurrence of climate change, while an additional 20% are disengaged or doubtful [*Maibach et al.*, 2009] (updated values available at https://climatecommunication-.yale.edu/about/projects/global-warmings-six-americas/). Moreover, 53% of those who disbelieve in climate change and 48% of those who are doubtful also disbelieve that climate scientists are in agreement over the occurrence and cause of the changes [*Doran and Zimmerman*, 2009]. This so-called 'consensus gap' is problematic in that the appearance of a lack of scientific consensus negatively impacts support for climate policy and societal action [*Ding et al.*, 2011; *Lewandowsky et al.*, 2013; *McCright et al.*, 2013]. Issues contributing to this gap include equal portrayal of scientists and climate deniers in the media [*Boykoff*, 2008; *Malka et al.*, 2009], skepticism based on pre-existing worldviews [*Lewandowsky et al.*, 2013; *McCright et al.*, 2013; *Campbell and Kay*, 2014], and anti-climate lobbying by interest groups [*Oreskes and Conway*, 2011].

Along with this skepticism, another factor contributing to incomplete buy-in or belief may be that school science for youth today may not always directly or completely address climate change in the classroom. In a study on 51 secondary students from the U.S. Midwest [*Shepardson et al.*, 2011], it was found that students' level of understanding of climate change vary significantly in sophistication and accuracy. Students expressed several misconceptions about the details surrounding greenhouse gases, air pollution, and weather. In fact, in a meta-analysis by *Choi et al.* [2010], a summary of 17 education research publications identified 41 commonly held misconceptions about climate change among students. Moreover, the authors reviewed 7 prevalent U.S. Earth and environmental science textbooks and found that most contained text and diagrams that could reinforce some of these.

Where formal education settings may not have yet had time to develop classroom curriculum appropriately responsive to the climate change crisis, outdoor environmental education programs (hereafter 'outdoor education' for brevity) may be primed to help fill the gap. Outdoor education offers opportunities to learn in, about, and for the outdoors [*Ford et al.*, 1986], combining the tenets of experiential and environmental education [*Adkins and Simmons*, 2002]. Experiential education centers on direct experience and in-context action, infused with critical reflection aimed at increasing knowledge and skills, and clarifying values [*Ford et al.*, 1986; *Kolb*, 2014]. Environmental education focuses on showcasing how natural environments function and how humans can act sustainably [*Stapp*, 1969; *Hungerford and Volk*, 1990; *Adkins and Simmons*, 2002], and carries as principal goals the preservation of a healthy, diverse ecosystem for future generations, and an engaged citizenry motivated to act on behalf of that goal [*Tanner*, 1980].

Much study has been devoted to examining the benefits of experiences outdoors to connecting people to the natural world. The study of environmental identity concerns itself with describing the ways in which people position themselves with respect to the non-human natural environment; it is both a product based on personal history, connection, and/or social influences, as well as a force that compels certain types of behavior toward the environment [*Clayton*, 2003]. Just as there exists a spectrum of views about climate change [*Maibach et al.*, 2009], so too is there a spectrum of environmental identities, ranging from those who do not necessarily relate to, connect with, and find value in conserving the natural world, to those who do and who will act on behalf of the environment in turn. One way it might be possible to help address the problem surrounding climate change skepticism and disengagement may be to facilitate experiences that help promote environmental identity development. In particular, providing opportunities for people to personally bear witness to a climate change-impacted landscape may help to shift attitudes by means of more strongly relating to a natural environment in flux.

Today, many outdoor education opportunities have begun to incorporate, and to study the benefits of, climate-related curriculum into their programming. Studies on the benefits of programming as diverse as overseas travel for youth to visit climate change-impacted locations and people [*Stapleton*, 2015] and engagement of tourists in climate-impacted landscapes in U.S. national parks and wildlife refuges [*Schweizer et al.*, 2013] have been found to increase salience and motivate environmental action. While the type of place-based lesson will vary depending on context and locale, climate change discussions in the U.S. North and Pacific Northwest often focus on rates of melt of the landscape's icy features, such as sea ice, permafrost, and glaciers. Glaciers in particular have in recent decades become a prominent symbol of climate change in popular media [*Doyle*, 2009; *Carey*, 2007], largely attributable to glaciers' dual connection to climate change both as archives of past climate that can be retrieved in ice cores, and as victims of rapid disintegration in current-day warming [*Carey*, 2007]. Beyond the media, different agencies and groups have also begun to recognize the potential of interactions with glaciers as a means for sharing knowledge about environmental change. The U.S. National Park Service is investing greater efforts to monitor glacier changes and to accordingly share these changes with tourists, given that (for example) in Alaska, 'glaciers are a central component of the visitor experience for many Alaskan parks' [*Loso et al.*, 2014]. Also within Alaska, nature-based tourism operators and tourists alike have been found to recognize the changes underway in the glaciers visited as part of their tour, and many share concerns over negative consequences for downstream environments and sea level rise [*Timm*, 2014].

From an environmental education perspective, changing glaciers are an opportunity. As glaciers continue to lose mass in a warming climate, it is not only invisible changes such as those to runoff biogeochemistry and timing that occur, but also visible impacts on surrounding landscapes. Over multi-year timescales, glacierized valleys undergo such changes as: glacier ice thinning and exposure of lateral moraines and nunataks (rock outcroppings), terminus retreat and exposure of new bedrock and till, formation of recessional end moraines, vegetation succession, slope destabilization, debris cover morphology (cliff, cave, and supraglacial stream formation), and outwash plain geomorphology [*Bennett and Glasser*, 2010]. Even without witnessing the passage of years, these signs of change are often highly visible on the surrounding landscape, and can often be dated, providing a tangible measure of the rate of a glacier's change. Because of this, glaciers have in recent decades become a prominent symbol of climate change in popular media [*Doyle*, 2009; *Carey*, 2007], largely attributable to glaciers' dual connection to climate change both as archives of past climate that can be retrieved in ice cores, and as victims of rapid disintegration in current-day warming [*Carey*, 2007].

1.5 Dissertation goals and approach

This dissertation addresses the dual need for assessing recent glacier mass loss in Alaska and resulting downstream impacts, and for exploring education strategies that leverage these changing glaciers to impact environmental identities. An integrative approach is proposed, where glacier change and environmental education research are not independent, but equally necessary components of an adaptable social-ecological system. In this introductory first chapter, I propose a conceptual framework for studying both the social and ecological components of rapid glacier change in Alaska, building on literature in resilience and adaptation strategies. In the second chapter, I describe the use of a coupled snow evolution and hydrological routing model for examining glacier mass balance and freshwater runoff for the Juneau Icefield in Southeast Alaska, in order to improve understanding of the coastal area's changing hydrological resources. In the third chapter, I compare modeled hydrological variables from the Mendenhall Glacier drainage to data from a nearby marine mooring in order to directly link glacial runoff to biogeophysical conditions in the nearshore marine environment. Finally, the fourth chapter analyzes qualitative social science data from youth participants in a science outreach program in a glacierized environment to track changes in environmental identity. Together, the geoscience and education research described here provides diverse perspectives on how to improve both scientific and citizen understanding of glacier mass changes in climate change.

1.6 Integrating glaciology and environmental education research

The work herein is not the first to explore glaciers from different perspectives, by asking what can be learned and leveraged from glaciers by observing not only biogeophysical data but human-glacier interactions as well. The works of Julie Cruikshank, anthropologist, have explored the cultural role that glaciers play in the lives of indigenous communities of the Yukon Territory in Northern Canada, who have historically used glaciers as travel corridors for passage through the mountain ranges of their homelands. In her book *Do Glaciers Listen? Local knowledge, colonial encounters, and social imagination*, the author describes how these communities think of glaciers as sentient beings, who respond directly and willfully to human behavior – for example, by surging, if disrespect is shown by speaking inappropriately in the presence of a glacier [*Cruikshank*, 2007]. In her book *The Secret Lives of Glaciers*, geographer M. Jackson similarly investigates the relationship between glaciers and the people who live among them, by interviewing Icelanders to better understand the societal and cultural impacts of ongoing changes to the northern nation's glaciers [*Jackson*, 2019]. Jackson describes the relationship as complex, rooted in personal and historical anecdotes, and once again containing hints of a belief in glaciers' sentience.

Despite these similarities, the response of different cultures to the presence and changing face of glaciers can vary broadly by place and community. In the book *Darkening Peaks: Glacier Retreat, Science, and Society*, anthropologist Ben Orlove and others point out how the cultural framing of glaciers ranges from one of respect (e.g. northern Canada and Iceland) to one of general avoidance of the cold and harsh environment (e.g. Ruwenzori Mountains, Uganda) to one of concern about climate change and the loss of ice to come (e.g. Val Bavona, Italy) [*Orlove et al.*, 2008].

Environmental historian Mark Carey has also written extensively on the varied roles that glaciers serve in broader society, whether as an evocative symbol – a geophysical 'endangered species' – that has emerged with increasing global dialogue about climate change [*Carey*, 2007], as a crucial and threatened water supply for rural and indigenous communities [*Carey*, 2010], or as a source of objective hazard like avalanche or outburst flood for exposed populations that dwell in their proximity [*Carey et al.*, 2012].

Carey's studies are also among the only works to propose conceptual frameworks for tackling these interdisciplinary topics in human-glaciological research. In their runoff modeling study on water resources in a case study watershed in Peru, Carey and others promote what they term a 'hydro-social' approach, stating it is "vital [for this type of research] to integrate the analysis of both water availability (the domain of hydrologists) and water use (the focus for social scientists)" [*Carey et al.*, 2014]. They posit that factors as diverse as political agenda, governance by law and institution, and land and resource use are all equally critical components in hydrological modeling in some regions of the world, given their profound impacts on water resources. In a different study, Carey and others propose a socio-environmental framework for glacier hazard management for nearby communities, pointing out the need for such elements as historical knowledge of past disaster events, technical capacity, institutional support, and committed individuals in order to implement successful mitigation tactics [*Carey et al.*, 2012]. Carey and others have even explored the role that gender plays in glaciological research. They ask glaciologists to consider how their own and others' research may be shaped by social realities such as a history of knowledge production dominated by (white/Western) men, as well as a system of scientific dominion that prevents representative knowledge contribution from developing nations or indigenous communities [*Carey et al.*, 2016]. Though different in scope, these conceptual frameworks each demonstrate how critically integrating individual elements of social and physical sciences can stimulate glaciological research that is both more holistic and actionable.

1.7 Advancing geoscience through lessons from ecology and resilience theory

Conceptual frameworks that scaffold holistic and actionable science are commonplace in ecological studies, and particularly studies concerned with observing or bolstering an ecosystem's resilience. Resilience is defined as the capacity of a system to absorb changes in ways that sustain and develop the same fundamental function, structure, identity, and feedbacks, either by recovery or reorganization of the system [*Chapin et al.*, 2009]. In an ecosystem context, resilience is a measure of how much disturbance – whether a shock or long-term perturbation, such as wildfire, human use, or climate change – an ecosystem can tolerate without changing into a qualitatively different state. Similarly, socio-cultural resilience is the ability of human communities to withstand and recover from stresses (like environmental change) without the loss of their fundamental culture, function, and identity. Resilience in societies and their life-supporting ecosystems is crucial in maintaining options not only for survival but for future human development [*Chapin et al.*, 2009].

For decades, ecologists investigating the ability of an ecosystem to demonstrate resilience have recognized the importance of considering not only ecological but also socio-cultural influences and implications within their research. *Berkes and Folke* [1994] were the first researchers to coin the term 'socio-ecological system' to describe an intrinsically coupled system of nature and people, as they sought to give equal weight to both components of the system in their analyses. The term aims to underscore that humans and human activity must be seen as a part of, not apart from, nature. Rather than perceive human actions and motivations as inherently distinct from traditional natural science approaches, socio-ecological systems theory recognizes that ecosystem health, changes, functions, and services are not only linked to but also shaped by humans [*Chapin et al.*, 2009].

In order to accurately capture this intrinsic interplay, ecologists began crafting conceptual frameworks that allow for simultaneous exploration of biophysical and socio-cultural data and methods towards a unified research goal. Doing so provides benefits such as: filling gaps between traditionally disparate subjects; coupling existing models to more accurately address complex questions; directing research efforts towards scientific outcomes with the greatest meaning for, relevance to, and impact on individuals and society.

One recent conceptual framework in particular was designed to examine social and ecological systems issues as a result of what the authors term 'press-pulse dynamics.' Envisioned as a tool for long-term ecological research into social-ecological system resilience, the press-pulse dynamics framework [*Collins et al.*, 2011] focuses on the impacts of external drivers on a social-ecological system, comprised of both biophysical and human/social elements, whereby pulse drivers are short-term natural or human-caused events such as drought or fire, and presses are long-term drivers of change such as climate change or increased resource consumption. In this framework, the external drivers act to influence the biophysical domain of the social-ecological system – both the ecosystem structure (i.e. how elements of the system are linked) as well as the ecosystem function (i.e. the role that the system plays within the broader context). Changes to the biophysical domain by the drivers then influence the system's ecosystem services, i.e. the availability, characteristics, or quality of the resources that the ecosystem provides. Because they define the quantifiable and qualitative benefits that humans derive from the social-ecological system [*Collins et al.*, 2011], these ecosystem services in turn impact the social domain of the system – both human outcomes (i.e. what humans receive from the ecosystem services) and human behavior (i.e. how the changes may instigate a human response). Human behaviors may then impact the external drivers even further, completing the loop via either amplifying or stabilizing feedbacks (i.e. either exacerbating or reducing the driving change and consequences) or by management of an alternative stable state [*Chapin et al.*, 2009]. All components of the framework are ultimately linked and have the ability to affect one another if perturbed, and all components must be examined to understand a system's resilience to change.

1.8 Conceptual framework for this dissertation

Turning the focus to geoscience fields such as glaciology, it is possible to build on both the above-described template [*Collins et al.*, 2011] and the work of holistic researchers like Carey to compose a framework for integrating geoscience and environmental education research that are both directed at better understanding the varied impacts of glacier loss. Figure 1.1 shows the conceptual framework I developed for this dissertation. The framework is designed to demonstrate how glaciological studies with hydrological, ecological, and environmental education applications can be approached as equally weighted components of an interconnected social-ecological system, whereby glaciers are impacted by humans via anthropogenic climate change, and humans are impacted by shrinking glaciers' ability to influence human behavior. In my framework, the principal **external drivers** being considered are climate change and growing social concern over environmental health, both of which have prompted much study, including the research I present in this dissertation. In the **short-term** (i.e. via pulse dynamics), the glacier-influenced ecosystem is perturbed by daily and seasonal variability, i.e. changes in snow pack, air temperature, and albedo. In the **long-term** (i.e. via press dynamics), the system responds to overall climatic changes, including increases in air temperature associated with high-latitude warming, and any detectable trends in rain and snow. These drivers influence the **biogeophysical domain** by modifying **ecosystem structure** (the overall hydrological cycle via changes in runoff timing and magnitude, and the physical landscape by glacier advance and retreat) and **ecosystem functions** (storage and release of freshwater, sediment and nutrient transport, biophysical controls on downstream ecosystems, and sea level rise moderation). Changes to these functions and structure modify the availability and quality of **ecosystem services** that glaciers provide to the social-ecological system, which fall in four categories: 1) **Regulating** (by maintaining ecosystem balance through controlling freshwater release and timing), 2) **Provisioning** (by providing freshwater and limiting nutrients downstream), 3) **Supportive** (by their role in maintaining downstream ecosystem health), and 4) **Cultural** (by their inherent value for cultures and recreation, and as an educational tool). Changes in these ecosystem services in turn influence the **social domain** of the social-ecological system, by impacting **human outcomes** (gaining knowledge capital for use in resource management decisions, opportunities for education about climate change, and opportunities for creating personal connection to landscape) and thereby **human behavior** (promotion of environmental stewardship activities, scientific and civic engagement, and administering appropriate resource management responses). Finally, these human behaviors then have the potential to influence the external drivers (i.e. the human-caused aspects of the pulse and press dynamics may be reduced or mitigated, in the ideal situation of a stabilizing feedback).

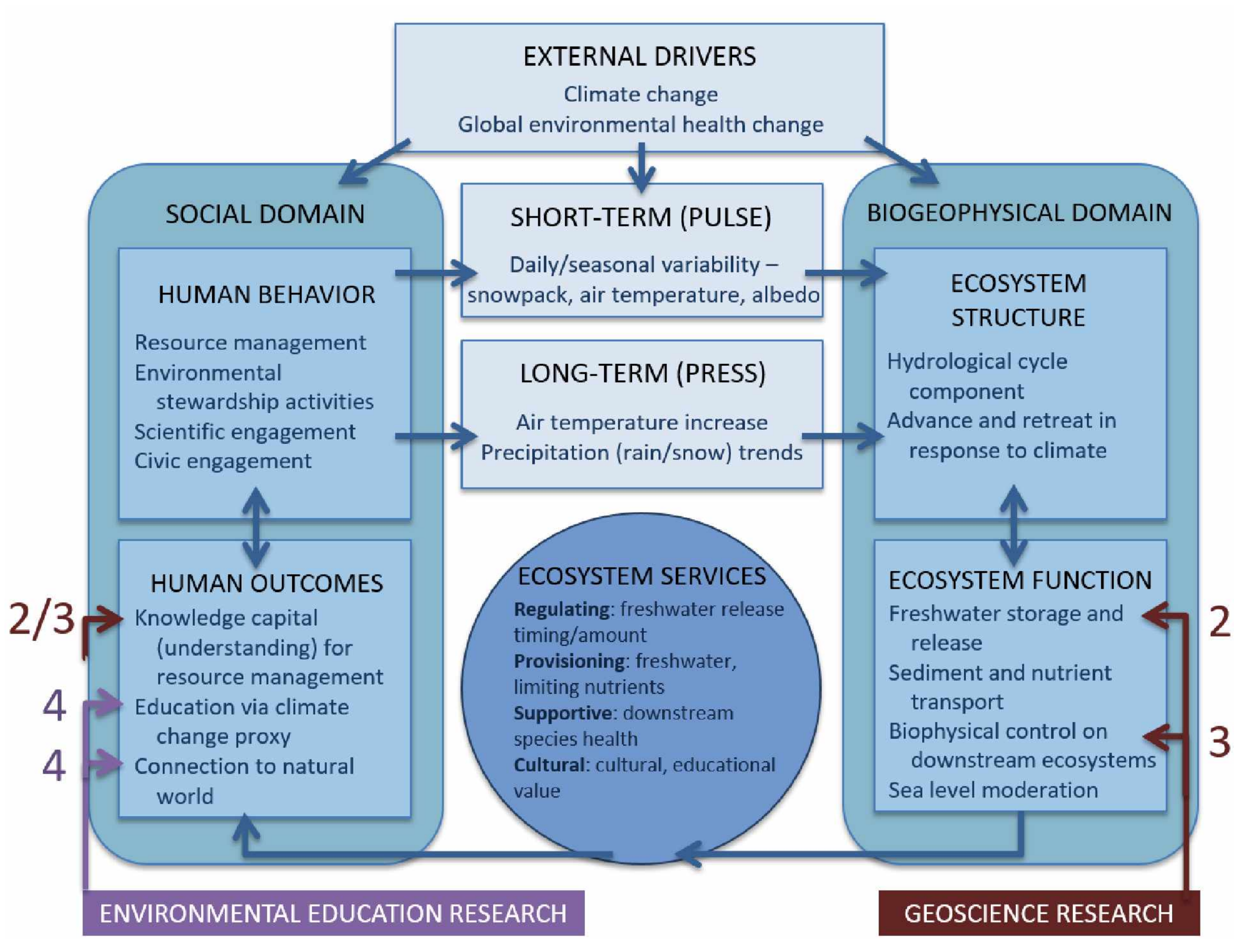

Figure 1.1: Socio-ecological framework for this dissertation.

This dissertation addresses five of the ecosystem functions and human outcomes mentioned in this conceptual framework (indicated in red and purple in Figure 1.1), which are connected by the ecosystem services that glaciers provide. First, Chapter 2 is focused on freshwater storage and release from glaciers (an ecosystem function), and in particular examines how long-term climatic changes (i.e. press dynamics) may be altering the timing and magnitude of that discharge. Chapter 3 examines glaciers' biophysical control on the downstream environment (an ecosystem function), by comparing modeled time series of glacier discharge to nearshore marine conditions. Both of these studies are motivated by a discussion of the critical ecosystem services that glaciers provide in each context, and also examine the utility of our findings for resource management (a human outcome). Finally, Chapter 4 explores two additional human outcomes: the educational opportunity provided by glaciers as a proxy for climate change, as well as the ability of experiences around glaciers to forge personal connection to the environment. Together, these multi-perspective studies provide insight into the varied roles that glaciers serve within an inextricably linked social-ecological system, and shed light on the potential for resilient response to change via resource management and education.

In ongoing climate change, it is not enough for the scientific community to add to the body of literature confirming glacier mass loss and expect that this alone communicates the need to prepare for downstream consequences. If the goal is a climate literate public able to engage meaningfully in developing appropriate mitigation policy and to adapt readily to ecosystem changes already set in motion, it is necessary to bridge the discontinuity between production and interaction with climate change information. This dissertation therefore aims to treat the changes underway in Alaska's glaciers as an opportunity for advancing not only science, but also strategies for disseminating that science through resource management recommendations and education.

1.9 References

Adkins, C., and B. Simmons (2002), *Outdoor, experiential, and environmental education: Converging or diverging approaches?*, ERIC Clearinghouse on Rural Education and Small Schools, AEL.

Arendt, A., J. Walsh, and W. Harrison (2009), Changes of glaciers and climate in northwestern North America during the late 20th century, *Journal of Climate*, *22*(15), 4117–4134.

Arendt, A., S. Luthcke, A. Gardner, S. O'Neel, D. Hill, G. Moholdt, and W. Abdalati (2013), Analysis of a GRACE global mascon solution for Gulf of Alaska glaciers, *Journal of Glaciology*, *59*(217), 913.

Arimitsu, M. L., J. F. Piatt, and F. Mueter (2016), Influence of glacier runoff on ecosystem structure in Gulf of Alaska fjords, *Marine Ecology Progress Series*, *560*, 19–40.

Barclay, D. J., G. C. Wiles, and P. E. Calkin (2009), Holocene glacier fluctuations in Alaska, *Quaternary Science Reviews*, *28*(21-22), 2034–2048.

Beamer, J., D. Hill, A. Arendt, and G. Liston (2016), High-resolution modeling of coastal freshwater discharge and glacier mass balance in the Gulf of Alaska watershed, *Water Resources Research*.

Bennett, M., and N. Glasser (2010), *Glacial Geology: Ice Sheets and Landforms, Second Edition*, 400 pp., Wiley.

Berkes, F., and C. Folke (1994), Linking social and ecological systems for resilience and sustainability, in *Workshop Property rights and the performance of natural Resource systems*.

Boykoff, M. (2008), Lost in translation? United States television news coverage of anthropogenic climate change, 1995–2004, *Climatic Change*, *86*(1-2), 1–11.

Campbell, T., and A. Kay (2014), Solution aversion: On the relation between ideology and motivated disbelief., *Journal of Personality and Social Psychology*, *107*(5), 809.

Carey, M. (2007), The history of ice: How glaciers became an endangered species, *Environmental History*, *12*(3), 497–527.

Carey, M. (2010), *In the shadow of melting glaciers: Climate change and Andean society*, Oxford University Press.

Carey, M., C. Huggel, J. Bury, C. Portocarrero, and W. Haeberli (2012), An integrated socio-environmental framework for glacier hazard management and climate change adaptation: Lessons from Lake 513, Cordillera Blanca, Peru, *Climatic Change*, *112*(3-4), 733–767.

Carey, M., M. Baraer, B. G. Mark, A. French, J. Bury, K. R. Young, and J. M. McKenzie (2014), Toward hydro-social modeling: Merging human variables and the social sciences with climate-glacier runoff models (Santa River, Peru), *Journal of Hydrology*, *518*, 60–70.

Carey, M., M. Jackson, A. Antonello, and J. Rushing (2016), Glaciers, gender, and science: A feminist glaciology framework for global environmental change research, *Progress in Human Geography*, *40*(6), 770–793.

Carnahan, E., J. Amundson, and E. Hood (2018), Impact of glacier loss on annual basin water yields, *Hydrology and Earth System Sciences Discussions*, pp. 1–20, doi:10.5194/hess-2018-509.

Chapin, F., M. Chapin, G. Kofinas, and C. Folke (2009), *Principles of Ecosystem Stewardship: Resilience-Based Natural Resource Management in a Changing World*, Earth and Environmental Science, Springer New York.

Choi, S., D. Niyogi, D. Shepardson, and U. Charusombat (2010), Do earth and environmental science textbooks promote middle and high school students' conceptual development about climate change?, *Bulletin of the American Meteorological Society*, *91*(7), 889.

Clayton, S. (2003), *Identity and the natural environment: The psychological significance of nature*, MIT Press.

Cohen, J., J. A. Screen, J. C. Furtado, M. Barlow, D. Whittleston, D. Coumou, J. Francis, K. Dethloff, D. Entekhabi, J. Overland, et al. (2014), Recent Arctic amplification and extreme mid-latitude weather, *Nature Geoscience*, *7*(9), 627–637.

Cohen, J. L., J. C. Furtado, M. A. Barlow, V. A. Alexeev, and J. E. Cherry (2012), Arctic warming, increasing snow cover and widespread boreal winter cooling, *Environmental Research Letters*, *7*(1), 014,007.

Collins, S. L., S. R. Carpenter, S. M. Swinton, D. E. Orenstein, D. L. Childers, T. L. Gragson, N. B. Grimm, J. M. Grove, S. L. Harlan, J. P. Kaye, et al. (2011), An integrated conceptual framework for long-term social–ecological research, *Frontiers in Ecology and the Environment*, *9*(6), 351–357.

Cook, J., N. Oreskes, P. T. Doran, W. R. Anderegg, B. Verheggen, E. W. Maibach, J. S. Carlton, S. Lewandowsky, A. G. Skuce, S. A. Green, et al. (2016), Consensus on consensus: A synthesis of consensus estimates on human-caused global warming, *Environmental Research Letters*, *11*(4), 048,002.

Criscitiello, A. S., M. A. Kelly, and B. Tremblay (2010), The response of Taku and Lemon Creek glaciers to climate, *Arctic, Antarctic, and Alpine Research*, *42*(1), 34–44.

Cruikshank, J. (2007), *Do glaciers listen?: Local knowledge, colonial encounters, and social imagination*, UBC Press.

Crusius, J., A. W. Schroth, S. Gasso, C. M. Moy, R. C. Levy, and M. Gatica (2011), Glacial flour dust storms in the Gulf of Alaska: Hydrologic and meteorological controls and their importance as a source of bioavailable iron, *Geophysical Research Letters*, *38*(6).

Crutzen, P. J. (2002), Geology of mankind, *Nature*, *415*(6867), 23.

Crutzen, P. J., and E. F. Stoermer (2000), Global change newsletter, *The Anthropocene*, *41*, 17–18.

Daly, C., M. Halbleib, J. I. Smith, W. P. Gibson, M. K. Doggett, G. H. Taylor, J. Curtis, and P. P. Pasteris (2008), Physiographically sensitive mapping of climatological temperature and precipitation across the conterminous United States, *International Journal of Climatology: A Journal of the Royal Meteorological Society*, *28*(15), 2031–2064.

De Woul, M., and R. Hock (2005), Static mass-balance sensitivity of Arctic glaciers and ice caps using a degree-day approach, *Annals of Glaciology*, *42*(1), 217–224.

Destouni, G., F. Hannerz, C. Prieto, J. Jarsjö, and Y. Shibuo (2008), Small unmonitored near-coastal catchment areas yielding large mass loading to the sea, *Global Biogeochemical Cycles*, *22*(4).

Ding, D., E. Maibach, X. Zhao, C. Roser-Renouf, and A. Leiserowitz (2011), Support for climate policy and societal action are linked to perceptions about scientific agreement, *Nature Climate Change*, *1*(9), 462–466.

Doran, P., and M. Zimmerman (2009), Examining the scientific consensus on climate change, *Eos, Transactions American Geophysical Union*, *90*(3), 22–23.

Dorava, J. M., and A. M. Milner (2000), Role of lake regulation on glacier-fed rivers in enhancing salmon productivity: The Cook Inlet watershed, south-central Alaska, USA, *Hydrological Processes*, *14*(16-17), 3149–3159.

Doyle, J. (2009), Seeing the climate?, *Ecosee: Image, Rhetoric, Nature*, pp. 279–298.

Dyurgerov, M., and M. Meier (2000), Twentieth century climate change: Evidence from small glaciers, *Proceedings of the National Academy of Sciences of the United States of America*, *97*(4), 1406–1411.

Fellman, J. B., S. Nagorski, S. Pyare, A. W. Vermilyea, D. Scott, and E. Hood (2014), Stream temperature response to variable glacier coverage in coastal watersheds of Southeast Alaska, *Hydrological Processes*, *28*(4), 2062–2073.

Fellman, J. B., E. Hood, P. A. Raymond, J. Hudson, M. Bozeman, and M. Arimitsu (2015), Evidence for the assimilation of ancient glacier organic carbon in a proglacial stream food web, *Limnology and Oceanography*, *60*(4), 1118–1128.

Ford, P., et al. (1986), Outdoor education: Definition and philosophy, *Resources in Education*, *21*(8).

Fountain, A. G., and W. V. Tangborn (1985), The effect of glaciers on streamflow variations, *Water Resources Research*, *21*(4), 579–586.

Gardner, A., G. Moholdt, J. Cogley, B. Wouters, A. Arendt, J. Wahr, E. Berthier, R. Hock, W. Pfeffer, G. Kaser, S. Ligtenberg, T. Bolch, M. Sharp, J. Hagen, M. van den Broeke, and F. Paul (2013), A reconciled estimate of glacier contributions to sea level rise: 2003 to 2009, *Science*, *340*(6134), 852–857, doi:10.1126/science.1234532.

Gleick, P. H., and M. Palaniappan (2010), Peak water limits to freshwater withdrawal and use, *Proceedings of the National Academy of Sciences*, *107*(25), 11,155–11,162.

Hill, D., N. Bruhis, S. Calos, A. Arendt, and J. Beamer (2015), Spatial and temporal variability of freshwater discharge into the Gulf of Alaska, *Journal of Geophysical Research: Oceans*, *120*(2), 634–646.

Hood, E., and L. Berner (2009), The effect of changing glacial coverage on the physical and biogeochemical properties of coastal streams in southeastern Alaska, *Journal of Geophysical Research*, *114*(13), G03,001, doi:10.1029/2009JG000971.

Hood, E., and D. Scott (2008), Riverine organic matter and nutrients in Southeast Alaska affected by glacial coverage, *Nature Geoscience*, *1*(9), 583–587.

Hood, E., J. Fellman, R. Spencer, P. Hernes, R. Edwards, D. D'Amore, and D. Scott (2009), Glaciers as a source of ancient and labile organic matter to the marine environment, *Nature*, *462*(7276), 1044–1048, doi:10.1038/nature08580.

Hungerford, H., and T. Volk (1990), Changing learner behavior through environmental education, *The Journal of Environmental Education*, *21*(3), 8–21.

Jackson, M. (2019), *The Secret Lives of Glaciers*, Green Writers Press.

Jansson, P., R. Hock, and T. Schneider (2003), The concept of glacier storage: A review, *Journal of Hydrology*, *282*(1-4), 116–129.

Kienholz, C., S. Herreid, J. Rich, A. Arendt, R. Hock, and E. Burgess (2015), Derivation and analysis of a complete modern-date glacier inventory for Alaska and northwest Canada, *Journal of Glaciology*, *61*(227), 403.

Kolb, D. (2014), *Experiential learning: Experience as the source of learning and development*, FT press.

Larsen, C. F., E. Burgess, A. A. Arendt, S. O'Neel, A. J. Johnson, and C. Kienholz (2015), Surface melt dominates Alaska glacier mass balance, *Geophysical Research Letters*, *42*(14), 5902–5908, doi:10.1002/2015GL064349.

Lewandowsky, S., M. Mann, L. Bauld, G. Hastings, and E. Loftus (2013), The subterranean war on science, *APS Observer*, *26*(9).

Lisi, P. J., D. E. Schindler, K. T. Bentley, and G. R. Pess (2013), Association between geomorphic attributes of watersheds, water temperature, and salmon spawn timing in Alaskan streams, *Geomorphology*, *185*, 78–86.

Liston, G. E., and C. A. Hiemstra (2011), The changing cryosphere: Pan-Arctic snow trends (1979-2009), *Journal of Climate*, *24*(21), 5691–5712.

Lorenz, J. M., and J. H. Filer (1989), Spawning habitat and redd characteristics of sockeye salmon in the glacial Taku River, British Columbia and Alaska, *Transactions of the American Fisheries Society*, *118*(5), 495–502.

Loso, M., A. Arendt, C. Larsen, j. Rich, and N. Murphy (2014), Alaska national park glaciers - status and trends - final report, *Technical report*, National Park Service.

Loso, M. G. (2009), Summer temperatures during the Medieval Warm Period and Little Ice Age inferred from varved proglacial lake sediments in southern Alaska, *Journal of Paleolimnology*, *41*(1), 117.

Lydersen, C., P. Assmy, S. Falk-Petersen, J. Kohler, K. M. Kovacs, M. Reigstad, H. Steen, H. Strøm, A. Sundfjord, Ø. Varpe, et al. (2014), The importance of tidewater glaciers for marine mammals and seabirds in Svalbard, Norway, *Journal of Marine Systems*, *129*, 452–471.

Maibach, E., C. Roser-Renouf, and A. Leiserowitz (2009), Global warming's six Americas 2009: An audience segmentation analysis.

Malka, A., J. Krosnick, M. Debell, J. Pasek, and D. Schneider (2009), Featuring skeptics in news media stories about global warming reduces public beliefs in the seriousness of global warming, *Woods Institute for the Environment, Stanford University, Technical Paper.*

Mann, M. E. (2002), Little Ice Age, *Encyclopedia of Global Environmental Change*, *1*, 504–509.

Mann, M. E., Z. Zhang, S. Rutherford, R. S. Bradley, M. K. Hughes, D. Shindell, C. Ammann, G. Faluvegi, and F. Ni (2009), Global signatures and dynamical origins of the Little Ice Age and Medieval Climate Anomaly, *Science*, *326*(5957), 1256–1260.

Masson-Delmotte, V., P. Zhai, H.-O. Prtner, D. Roberts, J. Skea, P. Shukla, A. Pirani, W. Moufouma-Okia, C. Pan, R. Pidcock, S. Connors, J. Matthews, Y. Chen, X. Zhou,

M. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (2018), IPCC, 2018: Summary for Policymakers. In: Global Warming of 1.5C. An IPCC Special Report on the impacts of global warming of 1.5C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty, *Technical report*, World Meteorological Organization.

McAfee, S. A., J. Walsh, and T. S. Rupp (2014), Statistically downscaled projections of snow/rain partitioning for Alaska, *Hydrological Processes*, *28*(12), 3930–3946.

McCright, A., R. Dunlap, and C. Xiao (2013), Perceived scientific agreement and support for government action on climate change in the USA, *Climatic Change*, *119*(2), 511–518.

Milner, A. M., and R. Bailey (1989), Salmonid colonization of new streams in Glacier Bay National Park, Alaska, *Aquaculture Research*, *20*(2), 179–192.

Moore, R. D., S. W. Fleming, B. Menounos, R. Wheate, A. Fountain, K. Stahl, K. Holm, and M. Jakob (2009), Glacier change in western North America: Implications for hydrology, geomorphic hazards and water quality, *Hydrological Processes*, *23*, 42–61.

Neal, E., E. Hood, and K. Smikrud (2010), Contribution of glacier runoff to freshwater discharge into Gulf of Alaska, *Geophysical Research Letters*, *37*(6), L06,404, doi:10.1029/2010GL042385.

O'Neel, S., E. Hood, A. Arendt, and L. Sass (2014), Assessing streamflow sensitivity to variations in glacier mass balance, *Climatic Change*, *123*(2), 329–341.

O'Neel, S., E. Hood, A. L. Bidlack, S. W. Fleming, M. L. Arimitsu, A. Arendt, E. Burgess, C. J. Sergeant, A. H. Beaudreau, K. Timm, et al. (2015), Icefield-to-ocean linkages across the northern Pacific coastal temperate rainforest ecosystem, *BioScience*, *65*(5), 499–512.

Oreskes, N., and E. Conway (2011), *Merchants of doubt: How a handful of scientists obscured the truth on issues from tobacco smoke to global warming*, Bloomsbury Publishing USA.

Orlove, B., E. Wiegandt, and B. H. Luckman (2008), *Darkening peaks: Glacier retreat, science, and society*, Univ of California Press.

Radić, V., and R. Hock (2014), Glaciers in the Earth's hydrological cycle: Assessments of glacier mass and runoff changes on global and regional scales, *Surveys in Geophysics*, *35*(3), 813–837.

Radić, V., A. Bliss, A. C. Beedlow, R. Hock, E. Miles, and J. G. Cogley (2014), Regional and global projections of twenty-first century glacier mass changes in response to climate scenarios from global climate models, *Climate Dynamics*, *42*(1-2), 37–58.

Roe, G. H., M. B. Baker, and F. Herla (2017), Centennial glacier retreat as categorical evidence of regional climate change, *Nature Geoscience*, *10*(2), 95.

Royer, T. (1981), Baroclinic transport in the Gulf of Alaska. Part II. A fresh water driven coastal current, *Journal of Marine Research*, *39*, 251–266.

Royer, T., C. Grosch, and L. Mysak (2001), Interdecadal variability of Northeast Pacific coastal freshwater and its implications on biological productivity, *Progress in Oceanography*, *49*(1), 95–111.

Schweizer, S., S. Davis, and J. Thompson (2013), Changing the conversation about climate change: A theoretical framework for place-based climate change engagement, *Environmental Communication: A Journal of Nature and Culture*, *7*(1), 42–62.

Screen, J. A., and I. Simmonds (2010), The central role of diminishing sea ice in recent Arctic temperature amplification, *Nature*, *464*(7293), 1334–1337.

Serreze, M. C., and R. G. Barry (2011), Processes and impacts of Arctic amplification: A research synthesis, *Global and Planetary Change*, *77*(1-2), 85–96.

Shepardson, D., D. Niyogi, S. Choi, and U. Charusombat (2011), Students' conceptions about the Greenhouse Effect, global warming, and climate change, *Climatic Change*, *104*(3-4), 481–507.

Stapleton, S. R. (2015), Environmental identity development through social interactions, action, and recognition, *The Journal of Environmental Education*, *46*(2), 94–113.

Stapp, W. (1969), The concept of environmental education, *Environmental Education*, *1*(1), 30–31.

Tanner, T. (1980), Significant life experiences: A new research area in environmental education, *The Journal of Environmental Education*, *11*(4), 20–24.

Timm, K. (2014), Nature-based tourism operator response to environmental change in Juneau, Alaska, Master's thesis, University of Alaska Fairbanks.

Weingartner, T. J., S. L. Danielson, and T. C. Royer (2005), Freshwater variability and predictability in the Alaska Coastal Current, *Deep Sea Research Part II: Topical Studies in Oceanography*, *52*(1), 169–191.

Welch, D., Y. Ishida, and K. Nagasawa (1998), Thermal limits and ocean migrations of sockeye salmon (Oncorhynchus nerka): Long-term consequences of global warming, *Canadian Journal of Fisheries and Aquatic Sciences*, *55*(4), 937–948.

Wiles, G. C., D. J. Barclay, and P. E. Calkin (1999), Tree-ring-dated 'Little Ice Age' histories of maritime glaciers from western Prince William Sound, Alaska, *The Holocene*, *9*(2), 163–173.

Chapter 2: A changing hydrological regime: Trends in magnitude and timing of glacier ice melt and glacier runoff in coastal glacierized watersheds[1]

2.1 Abstract

With a unique biogeophysical signature relative to other freshwater sources, meltwater from glaciers plays a crucial role in the hydrological and ecological regime of high latitude coastal areas. Today, as glaciers worldwide exhibit persistent negative mass balance, glacier runoff is changing in both magnitude and timing, with potential downstream impacts on infrastructure, ecosystems, and ecosystem resources. However, runoff trends may be difficult to detect in coastal systems with large precipitation variability. Here, we use the coupled energy balance and water routing model SnowModel-HydroFlow to examine changes in timing and magnitude of runoff from the western Juneau Icefield in Southeast Alaska between 1980 to 2016. We find that under sustained glacier mass loss (-0.57 $\pm$ 0.12 m w.e. a^{-1}), several hydrological variables related to runoff show increasing trends. This includes annual and spring glacier ice melt volumes (+10% and +16% decade^{-1}) which, because of high precipitation variability in the area, translate to smaller increases in glacier runoff (+3% and +7% decade^{-1}) and total watershed runoff (+1.4% and +3% decade^{-1}). These results suggest that the western Juneau Icefield watersheds are still in an increasing glacier runoff period prior to reaching 'peak water.' In terms of timing, we find that maximum glacier ice melt is occurring earlier (2.5 days decade^{-1}), indicating a change in the source of freshwater being delivered downstream. Our findings highlight that even in climates with large precipitation variability, high latitude coastal watersheds are experiencing hydrological regime change driven by ongoing glacier mass loss.

[1]Young, J.C., Pettit, E., Arendt A., Hood, E., Liston, G.E., and J. Beamer (2020). *A changing hydrological regime: Trends in magnitude and timing of glacier ice melt and glacier runoff in a high latitude coastal watershed.* Manuscript submitted for publication.

2.2 Introduction

Meltwater from glaciers plays a crucial and varied role in both the hydrological and ecological regimes of high latitude coastal regions around the world. From a hydrological perspective, glaciers act as frozen freshwater reservoirs, with the ability to temporarily store water over diurnal, seasonal, and long-term (decadal to millennial) time scales [*Jansson et al.*, 2003]. Watersheds containing even as little as 5% glacier cover exhibit modified flow patterns compared to their ice-free equivalents, with lower annual and monthly variability, and with a maximum seasonal flow contemporaneous not with spring snowmelt but with peak temperatures in mid-summer [*Fountain and Tangborn*, 1985]. These differences arise because while runoff from non-glacierized watersheds is dominated by precipitation, glacierized basins are primarily energy balance dominated [*Lang*, 1986].

Additionally, watersheds downstream of glaciers with persistent negative net mass balance display a distinct long-term streamflow pattern. This pattern is characterized initially by increasing discharge due to higher rates of glacier mass loss up until a maximum (often referred to as 'peak water' [*Gleick and Palaniappan*, 2010]), followed by decreasing discharge due to shrinking glacier area and volume [*Jansson et al.*, 2003]. Whether or not a glacierized basin or region has passed peak water is linked to several factors. *Huss and Hock* [2018] found through a global glacier mass balance modeling study that characteristics such as percent ice cover and glacier size exhibit controls over the timing of peak water in a basin. Similarly, *Moore et al.* [2009] identified geographic variations in runoff trends for Western North American glacierized basins, whereby basins with larger glaciers in the north still show increasing runoff while basins with smaller glaciers further south have already passed the point of peak water. On the other hand, *Carnahan et al.* [2018] identified through glacier flow modeling that glacier dynamics (characterized by glacier response times, linked primarily to climate and slope) and landscape evolution (i.e. vegetation succession after deglaciation) had a roughly equal impact on basin runoff in response to glacier retreat. Together, these findings indicate that peak water is likely to occur at different times in different regions.

Knowing whether an area is pre- or post-peak water is crucial information in glacierized watershed hydrology, due to the implications of increasing or decreasing runoff for downstream concerns such as infrastructure, ecosystems, and ecosystem resources [*Moore et al.*, 2009]. In a study that forecast glacier streamflow to 2100, the large glaciers of the Gulf of Alaska were predicted to experience peak water the latest (between 2060 and 2070) of all regions globally [*Huss and Hock*, 2018]. However, the fate of individual glacierized watersheds within this region was less certain due to large intrabasin variability and calibration to regional glacier mass balance observations rather than local runoff measurements.

Within the Gulf of Alaska region lies the Juneau Icefield, one of the largest icefields in North America. This area experiences extreme amounts of precipitation characteristic of maritime climates [*Pelto et al.*, 2013], and among the highest variability in precipitation of any climatic zone in Alaska [*Bieniek et al.*, 2014], both of which may act to obscure runoff trend detection. The icefield is directly adjacent to the city of Juneau, Alaska, and is closely connected to both the community's infrastructure (via bridges over glacial rivers and residential areas prone to flooding from glacial outburst floods) as well as to the downstream riverine and nearshore marine environments.

From an ecological perspective, freshwater from glaciers – whether from melted glacier ice, melted firn, or terrestrial water that has passed through a glacier system – carries a unique biogeochemical signature relative to other freshwater sources. For example, glacier runoff has been found to control fluxes of limiting nutrients crucial for primary productivity in riverine and marine environments. A previous study on streams discharging the Juneau Icefield found that glaciers serve as an important source of phosphorus and nitrogen in those streams [*Hood and Scott*, 2008], while nearby rivers such as the Copper River have proven a critical source of iron to the Gulf of Alaska [*Crusius et al.*, 2011]. Glacier meltwater also serves as a major source of bioavailable organic carbon to both riverine food webs [*Fellman et al.*, 2015] and near-shore marine ecosystems [*Hood et al.*, 2009; *Lawson et al.*, 2014]. Moreover, glacier runoff possesses physical properties that are distinct from other terrestrial water sources. In comparing several Juneau Icefield watersheds, *Hood and Berner* [2009] show that both summer stream turbidity and water temperature can be predicted by the percentage of glacier cover within the basin. These physical conditions are in turn critical for biological productivity at all trophic levels, including for Pacific salmon (*Oncorhynchus* spp.) for which stream temperature and clarity are key variables for species distribution in the north Pacific [*Welch et al.*, 1998] as well as spawning ground selection [*Lorenz and Filer*, 1989].

To assess changes in this physical landscape, several studies have evaluated glacier mass balance of the Juneau Icefield in recent decades. These have primarily relied on geodetic approaches (e.g. digital elevation model differencing) that determine bulk volume loss between two known dates. Despite sourcing imagery from different satellite sensors and covering different time spans, all studies calculated negative glacier-wide mass balance rates over the investigated periods between 1962 to 2016 [*Larsen et al.*, 2007; *Berthier et al.*, 2010; *Melkonian et al.*, 2014; *Berthier et al.*, 2018]. A recent study has also modeled future glacier mass balance for the icefield under different climate scenarios, projecting a volume loss of 58 to 68% of the icefield by 2100 [*Ziemen et al.*, 2016]. This estimate falls on the upper end of regional projections of a 32 to 58% loss of Gulf of Alaska glaciers as a whole [*Hock and Huss*, 2015].

Given the aforementioned close coupling to surrounding ecosystems and infrastructure, and its persistent state of negative mass balance, the purpose of this study is to examine whether and how components of runoff from the western Juneau Icefield have changed over the past several decades. In particular, we leverage a distributed, high-resolution model to evaluate: 1) trends in the annual or seasonal volume of total runoff, glacier runoff, and glacier ice melt; 2) shifts in timing of the onset or end of glacier runoff and/or ice melt season; 3) shifts in winter glacier runoff events or volume, and 4) changes in timing or magnitude of total runoff, glacier runoff, and glacier ice melt. This study is the first to examine recent changes in timing and magnitude of different hydrological cycle variables in this region and, in turn, to assess whether trends of increasing or decreasing runoff can be detected in a high latitude maritime environment. These findings provide key information for socio-ecological systems downstream, and leave us better poised to project future changes in ongoing climate change.

2.3 Study area

Bordered by mountain ranges spanning from sea level to >5000 m a.s.l., and with a maritime climate that delivers an average of 2 m w.e. and a peak of 7 m w.e. of precipitation per year [*Daly et al.*, 2008], the Gulf of Alaska coastline is characterized by both extensive glacier cover and extreme volumes of freshwater runoff. Unlike other major watersheds in North America that are dominated by large rivers, 78% of runoff into the Gulf of Alaska is delivered from the steep topography to the coast via short (∼10 km average), small drainages [*Neal et al.*, 2010]. In coastal Alaska, glacier termini often lie below treeline, placing glacier ice directly adjacent to the mixed forest of the northern Pacific temperature rainforest. Together, these qualities set up a tight coupling between ice and snowmelt from alpine terrain and the nearshore marine ecosystems downstream.

The Juneau Icefield (Figure 2.1), centered at 58.9° N and 134.2° W, spans the coast mountains between Southeast Alaska, USA, and Northwestern British Columbia, Canada. It is the third largest icefield in North America with an area of >3700 km^2 and elevations ranging from sea level to ∼2300 m a.s.l [*Kienholz et al.*, 2015]. All outlet glaciers are currently lake- or land-terminating although, as it finishes a tidewater glacier cycle advance [*Truffer et al.*, 2009], the large (∼725 km^2) Taku Glacier is ∼60% protected by a shoal moraine with the remaining portion of the terminus abutting a proglacial lake and short river.

Although the highest elevations receive snowfall throughout the year, C-band synthetic-aperture radar reveals that snow and/or ice melt occurs over the entire icefield during July and August [*Ramage et al.*, 2000]. Moreover, because temperatures frequently hover near the freezing point on the coast, low elevations may see ice melt and rain throughout the year.

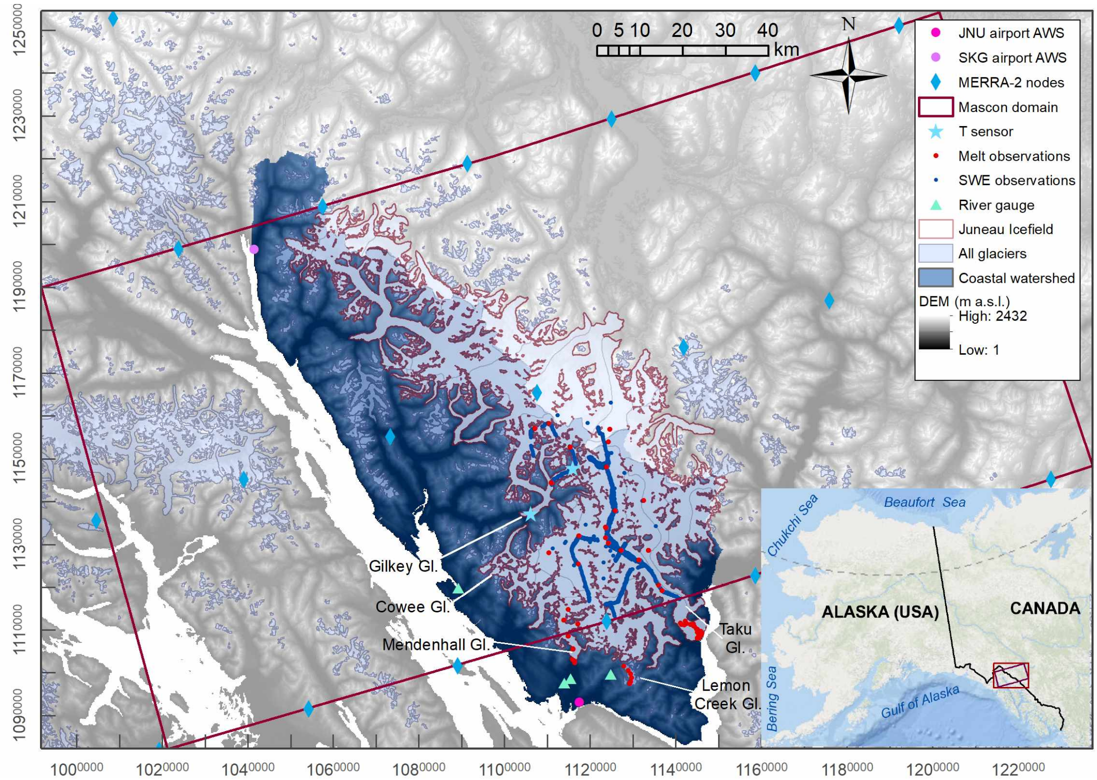

Figure 2.1: Location of the Juneau Icefield within the Coast Mountains of southeast Alaska and northern British Columbia, showing all field and remotely sensed datasets used in model calibration. All glaciers within the rectangular model domain are shown in light blue, and the contiguous glaciers of the Juneau Icefield as defined in the Randolph Glacier Inventory version 6.0 are outlined in red. Also shown are: locations of automated weather stations at each the Juneau (JNU) and Skagway (SKG) airports; MERRA-2 reanalysis climate nodes; the mascon domain showing the area of GRACE solutions used for model validation; campaign on-ice temperature sensors; observations of melt and snow water equivalent (SWE); and stream gauge stations. Terrain shown in dark blue indicates the spatial extent of our coastal watershed domain for this study.

In addition to typical patterns of increasing precipitation with elevation, the icefield also experiences a strong decreasing precipitation gradient from southwest to northeast (i.e. with increasing distance from the coast) due to the prevalence of southwesterly weather systems moving inland from the Gulf of Alaska [*Royer*, 1998; *Stabeno et al.*, 2004]. These patterns are evidenced both in measurements [*Pelto et al.*, 2013] and mass balance modeling studies [*Ziemen et al.*, 2016; *Roth et al.*, 2018].

The spatial domain in this study comprises all terrain draining the western portion of the Juneau Icefield directly to the coast. Though we calculate glacier mass balance for the entire icefield for purposes of calibration, we focus our calculations and analysis of runoff on those watersheds of the icefield that supply direct runoff to marine ecosystems. This amounts to a spatial domain of 6405 km^2, of which 2860 km^2 or 44% is glacier ice covered.

2.4 Data & methods

In remote and rugged settings where the availability of ground observations is scarce and long-term hydro-climatic monitoring stations are few, glacio-hydrological models can help fill knowledge gaps about the hydrological regime at high spatial and temporal resolution. To estimate glacier mass balance and total runoff at a daily time step for water years 1981 to 2016 for the Juneau Icefield, we use the energy and mass balance model SnowModel [*Liston and Elder*, 2006a], coupled with the SoilBal routine for calculating evapotranspiration over all ice-free domains [*Beamer et al.*, 2016], and the linear reservoir runoff routing model HydroFlow [*Liston and Mernild*, 2012]. These model routines, including sub-modules we used, are described below, as are the data and approaches used for initialization, calibration, and validation.

2.4.1 Model description

SnowModel SnowModel is a distributed energy and mass balance model for simulating snow distribution and evolution in terrain where snow and ice are present [*Liston and Elder*, 2006a]. It uses meteorological, elevation, and surface type data as inputs, and accounts for all first-order processes involved in snowpack evolution, including: snow accumulation; forest canopy interception, unloading, and sublimation; snow-density evolution; and snowpack and ice melt. SnowModel is comprised of several sequential sub-routines: 1) MicroMet, 2) EnBal, and 3) SnowPack.

MicroMet is a quasi-physically-based data assimilation and interpolation routine that distributes coarse-resolution meteorological forcing over high-resolution topography [*Liston and Elder*, 2006b]. MicroMet adjusts coarse-resolution climate data in two ways: a) all available data are spatially interpolated over the domain, and b) physical submodels are applied to each variable to generate more realistic values at each grid cell and time step. MicroMet also estimates solar and incoming longwave radiation based on topography and cloud cover based on relative humidity and temperature.

EnBal performs surface energy balance calculations at every grid cell, in response to atmospheric conditions generated in MicroMet. Energy terms are added at the snow- or ice-atmosphere interfaces, and any surplus energy is assumed to be available for snowmelt, or for glacier ice melt once overlying snow has been removed [*Mernild et al.*, 2006].

SnowPack simulates snow depth and snow water equivalent evolution based on precipitation and melt energy. Snow density changes in response to snow temperature and the weight of overlying snow, as well as by snow melting and rain-on-snow events, which redistribute water through the snowpack. Further details on both EnBal and SnowPack are available in *Liston and Elder* [2006a], and on MicroMet in *Liston and Elder* [2006b].

SnowModel does not include a glacier flow model to redistribute mass under climate forcing. To avoid infinite snow accumulation at high elevations over glacier cells during multi-year simulations, each year's end-of-summer snowpack over glacier cells is reset to zero under the assumption that residual snow is converted to glacier ice. SnowModel also does not account for changes in either glacier extent by retreat or hypsometry (area-altitude distribution) by thinning or ice flow and instead keeps a constant surface and extent representing conditions during a reference year/period (Section 2.4.2). See Section 2.7 for further examination of this limitation. Moreover, while SnowModel includes many internal processes within the snowpack related to density changes and meltwater percolation, it neglects snow and ice mass loss due to dynamic processes, such as frictional melting from viscous heating (internal deformation of the ice) or sliding at the glacier bed [*Mernild et al.*, 2014].

SnowModel has been applied in a number of Arctic glaciology investigations at similar spatial scales as our study, including in Alaska and Greenland [*Liston and Sturm*, 2002; *Mernild et al.*, 2006, 2007, 2010; *Liston and Hiemstra*, 2011; *Mernild et al.*, 2015, 2017]. Recently, SnowModel has also been applied along with the SoilBal and HydroFlow routines to model freshwater discharge from 1980 to 2014 for all terrain draining into the Gulf of Alaska [*Beamer et al.*, 2016], a study which informs several of our model configuration choices.

SoilBal SoilBal, a soil moisture submodel, was developed by *Beamer et al.* [2016] to formally introduce evapotranspiration (ET) into the SnowModel-HydroFlow process, in order to allow for full water balance calculations over ice-free landscapes, including vegetation. SoilBal first calculates potential evapotranspiration (PET) by means of the Priestley-Taylor equation, which is based on the concept that an air mass moving over a vegetated landscape with abundant water will become water saturated [*Priestley et al.*, 1972]. It uses only daily air temperature and net radiation for the top of the canopy as input data, making it more computationally efficient than complex formulations that include aerodynamic terms. The Priestley-Taylor formulation has been applied to many types of forested landscapes (see *Komatsu* [2005] for a review of studies) and has been found to outperform more complex formulations for a mixed temperate mountainous forest [*Shi et al.*, 2008]. After PET is calculated, a soil water balance [*Hoogeveen et al.*, 2015] is solved using inputs of PET, runoff from SnowModel, and gridded soil water storage. SoilBal ultimately produces daily grids of actual evapotranspiration, surface, and base flow runoff. The latter two are summed and used to drive the water routing model HydroFlow.

HydroFlow Using instantaneous water balance information from SnowModel and SoilBal, the HydroFlow model simulates the routing of surface runoff from rainfall, snow, and ice melt to downslope areas and ultimately to basin outlets or surrounding oceans [*Liston and Mernild*, 2012; *Mernild and Liston*, 2012]. In HydroFlow, each grid cell acts as a linear reservoir (i.e. a reservoir with discharge linearly proportional to water input) that transfers water from itself and any upslope cells to the downslope cell, creating a topographically linked flow network. HydroFlow assumes that within each grid cell there are two transfer functions with two time scales, each associated with different water routing mechanisms. Runoff enters first into the slow-response reservoir, which accounts for the time it takes for water transport through the snow, ice, and soil matrices. The moisture is then routed through the flow network via the fast-response reservoir, which generally represents some form of channel flow, such as supra-, en- or subglacial flow, or streamflow. Residence time coefficients for each reservoir in each grid cell are a function of many elements, including: surface slope; snow, ice, and soil porosity; snow temperature (cold content); density of glacier crevasses and moulins; hydrostatic water pressure; and soils and land-cover characteristics. HydroFlow therefore assigns residence time coefficients and velocities for four dominant surface types that account broadly for these processes: snow-covered ice, snow-free ice, snow-covered land, and snow-free land. A coupled system of equations solves for slow- and fast-response flow, yielding a discharge hydrograph for each grid cell. A full description of HydroFlow is available in *Liston and Mernild* [2012].

2.4.2 Model configuration

Our model simulations cover the water years between Oct. 1, 1980 to Sept. 30, 2016 and are run using a daily time step and grid cell size of 200 m x 200 m. The chosen temporal and spatial resolution represent a compromise between the desired level of detail and computational efficiency, given the large spatial domain.

Figure 2.1 shows our model spatial domain, which encompasses the full extent of all observational datasets used for calibration and validation (described below). For this study's results and interpretation, unless otherwise specified, reported findings on glacier mass balance include model grid cells within the red outline of the Juneau Icefield, in order to match estimates from both *Berthier et al.* [2018], used in model calibration, and *Ziemen et al.*

[2016], which we refer to in our discussion of future changes. However, when reporting findings on freshwater runoff, we include in our spatial domain all terrain with Juneau Icefield glacier ice in its headwaters that drains directly to the coast. We do not include terrain that routes freshwater into large interior rivers (Taku River, with a drainage area of 17,000 km^2, and the Yukon River, 850,000 km^2). We exclude these regions for two reasons. First, the size of these river drainages is sufficiently different than the short, steep coastal drainages of the western portion of the Icefield (e.g. the basin drained by the Mendenhall River is the largest at 289 km^2) and therefore exemplify different watershed processes. Second, Taku and the Yukon drain primarily continental terrain subject to a different climatological regime, given that they lie in (and well beyond) the rainshadow of the Coast Mountain range that creates a strong precipitation gradient from coast to interior [*Roth et al.*, 2018]. We focus our analysis and discussion on the unique hydrological regime of the short and steep coastal drainages, particularly given their relevance to downstream estuary conditions, and their prevalence throughout high latitude coastal regions in Alaska (e.g. Glacier Bay, Prince William Sound) and beyond (e.g. Patagonia, New Zealand, Norway).

To evolve the snowpack and route water through the landscape, SnowModel-HydroFlow requires topographical data, land cover information, and meteorological forcing.

Elevation, land cover, and soil type For model simulations, we use a digital elevation model (DEM) from the United States Geological Survey (USGS) National Elevation Dataset (available at https://nationalmap.gov/elevation.html), representing elevations from the early 2010s as measured by Interferometric Synthetic Aperture Radar. Data are available at a resolution of 1 arcsec (∼30 m) over ∼95% of the domain, and 2 arcsecs (∼60 m) over portions of Canada for which a better resolution is not available. The DEM is hydrologically corrected (i.e. depressionless) and we resample to 200 m resolution using a nearest-neighbor sampling technique. Note that we do not modify glacier surface elevations or extents through the 1980 to 2016 model period given that earlier DEMs for the full icefield are not available.

Land cover classes are obtained from the 2011 North American Land Change Monitoring System (NALCMS), which distinguishes vegetation class, bare land, and urbanized area for North America at a 30 m resolution [*Homer et al.*, 2015]. We resample to 200 m and align the grid with our DEM and reclassify to the vegetation classes defined in *Liston and Elder* [2006a]. To delineate glacierized terrain, we modify the NALCMS grid using higher precision glacier outlines derived from the mid-2000s from the Randolph Glacier Inventory (RGI) v6.0, available at https://www.glims.org/RGI/rgi60_dl.html [*Pfeffer et al.*, 2014; *Kienholz et al.*, 2015]. Note that over our model period, we do not update surface type information related to e.g. vegetation succession after deglaciation, due to a lack of information on glacier and vegetated area extent dating back to the 1980s.

To classify soil types, we use the gridded Harmonized World Soil dataset version 1.2 (available at http://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/harmonized-world-soil-database-v12/en/) [*Fischer et al.*, 2008], which we resample from its native 1 km resolution to 200 m using a nearest-neighbor technique.

For the SoilBal soil moisture module, we use a Priestley-Taylor coefficient of 1.26, a value found by *Beamer et al.* [2016] to reproduce modeled ET for the Gulf of Alaska that most closely matches independent estimates from the Moderate Resolution Imaging Spectroradiometer (MODIS) satellite product as found in *Hill et al.* [2015].

Meteorological data For meteorological forcing, SnowModel requires daily temperature, relative humidity, wind speed and direction, and precipitation. We use reanalysis data from NASA's Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2) [*Gelaro et al.*, 2017], available at http://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/. One of our principal motivators in choosing this product is that in their modeling study on freshwater runoff to the Gulf of Alaska, *Beamer et al.* [2016] found that Version 1 of MERRA [*Rienecker et al.*, 2011] performed best in reproducing measurements of point glacier mass balance and local domain streamflow, compared to the Climate Forecast System Reanalysis

Saha et al. [2010] and North American Regional Reanalysis [*Mesinger et al.*, 2006]. Version 1 of MERRA was also among the top products for consistency with observations of 2 m air temperature and precipitation [*Lindsay et al.*, 2014], and compared best to observed extreme precipitation days at the Juneau airport [*Lader et al.*, 2016], in two studies that compared different climate products for the Arctic and Alaska, respectively. Moreover, MERRA-2 has been found to perform better in North America than the earlier MERRA version for precipitation, and snow amounts in particular have been found to have a lower bias and better correlation to reference data in neighboring parts of Canada [*Reichle et al.*, 2017]. Altogether, these findings encouraged our choice of this product as model forcing.

We compare the product to observational meteorological records within our domain and discuss the outcomes in Section 2.5.

2.4.3 Model calibration datasets

To help constrain our estimates of glacier mass change and freshwater runoff for the Juneau icefield, we use multiple calibration datasets including: a geodetic glacier mass balance estimate, streamflow measurements, snow water equivalent observations, and ablation observations.

Geodetic glacier mass balance Several studies have derived geodetic bulk volume loss estimates for the Juneau Icefield, including *Larsen et al.* [2007] who estimated -0.62 m w.e. a^{-1} for 1962 to 2000, *Berthier et al.* [2010] who found -0.53 ± 0.15 m w.e. a^{-1} for 1962 to 2006, *Melkonian et al.* [2014] who found -0.13 ± 0.12 m w.e. a^{-1} for 2000 to 2009/2013, and *Berthier et al.* [2018] who estimated -0.68 ± 0.15 m w.e. a^{-1} for 2000 to 2016. Though the *Melkonian et al.* [2014] study initially suggested a slowdown in mass loss, *Berthier et al.* [2018] points to issues in *Melkonian et al.* [2014] related to unknown penetration depths into firn and snow by the Shuttle Radar Topography Mission DEMs used in their calculations. The mass balance result from *Berthier et al.* [2018], calculated from Advanced Spaceborne Thermal

Emission and Reflection Radiometer (ASTER) imagery, agrees closely with laser altimetry approaches and is therefore the value we take as the current best estimate overlapping with our study interval.

In our calibration process, we aim to reproduce the mean annual glacier-wide mass balance rate from *Berthier et al.* [2018] for the same spatial domain (i.e. the glacier outline for the Juneau Icefield, which the authors also obtained from the Randolph Glacier Inventory v6.0). Because the early and late ASTER scenes used in *Berthier et al.* [2018] represent mosaics of different acquisition dates, the authors listed their geodetic estimate as generally spanning 2000 to 2016, without citing specific start or end dates. For comparison to the model, we select start and end dates as the beginning and end of the associated water years, i.e. Oct. 1, 2000 and Sept. 30, 2016.

Streamflow measurements Semi-continuous time series of discharge data are available for four stream gauges in the Juneau area, including three streams instrumented by the USGS (Mendenhall River, Lemon Creek, and Montana Creek; data available at https://waterdata-.usgs.gov/nwis/rt) and one (Cowee Creek) monitored by researchers at the University of Alaska Southeast (Figure 2.1). Data are available for different time periods for each. The four instrumented basins represent a range of size above the gauge locations, percent glacier cover, elevation range, and distance between glacier outflow and gauge (Table 2.1). This range of characteristics increases our ability to test model performance across different flow regimes. In our calibration process, we aim to reproduce discharge (Q) from all upstream terrain as routed to the gauge locations.

Snow water equivalent Point observations of snow water equivalent (SWE) used to drive SnowAssim (Figure 2.1) are obtained from several published and unpublished sources. All values are converted to SWE following standard glaciological protocols [*Østrem and Brugman*, 1991]. We glean observations for Taku Glacier and Lemon Creek Glacier from *Criscitiello et al.* [2010], and for Mendenhall Glacier from *Motyka et al.* [2002] and *Boyce et al.*

Table 2.1: Characteristics of gauged watersheds included in calibration routine

River	Area (km^2)	Glacier cover (%)	Elevation range (m a.s.l.)	Distance between glacier outflow and gauge	Gauge data availability
Mendenhall River	223	56	20 to 1980	5 km with large lake	1980 to 1994; 1996 to 2016
Lemon Creek	31	46	280 to 1620	4 km	2002 to 2016
Montana Creek	36	2	20 to 1480	12 km	1980 to 1987; 2000 to 2012
Cowee Creek	111	11	0 to 1700	15 km with small lake	2013 to 2016

[2007]. Additional observations are also available for Taku [*McNeil et al.*, 2019a] and Lemon Creek glaciers [*McNeil et al.*, 2019b], Taku Glacier (University of Alaska Southeast, Jason Amundsen, unpublished data), and Mendenhall Glacier (University of Alaska Southeast, Mike Hekkers, unpublished data).

During several field campaigns in late April of 2013, 2014, and 2015, our team also carried out SWE observations at six locations along the Gilkey Glacier centerline between 300 to 1900 m a.s.l., as a means to fill in spatial gaps over the icefield. SWE values were derived using measured density profiles obtained from snow core samples, representing stratigraphic balances. Data are available at *Young* [2019].

Finally, we also incorporate helicopter-borne ground-penetrating radar (GPR) observations collected by USGS along the Taku Glacier and Gilkey Glacier centerlines in spring 2014 and 2015, in collaboration with our field campaigns. Raw GPR data were sourced from *O'Neel et al.* [2018], and were processed by USGS and converted to snow depths using the methods described in *McGrath et al.* [2015]. Density data were sourced from six contemporaneous snow cores measured along each corresponding flight path, where densities were linearly interpolated between locations by the increment $1/n$, where n is the number of ~equally-spaced observations between core sites. By multiplying depths by densities, this dataset is equivalent to ~121,000 and ~39,000 SWE point observations in 2014 and 2015, that we averaged to single annual values within each model grid cell.

Ablation observations For our calibration routine, we also make use of point snow and ice ablation observations at stake sites from the published and unpublished datasets described in Section 2.4.3. We also leverage melt data from our own field campaigns in 2013 to 2015, available at *Young* [2019]. Snowmelt values were calculated by subtracting the SWE equivalent values between snowpacks at known start and end dates. Ice melt values used exposed stake height changes multiplied by an assumed glacier ice density of 900 kg m^{-3}. All ablation observations are compared to model output extracted for the same location and covering the same time span.

2.4.4 Calibration approach

To correctly characterize glacier mass change and freshwater discharge, we adopt a two-stage calibration approach. The first stage is automated within SnowModel, and leverages the built-in data assimilation sub-routine SnowAssim. SnowAssim is used to compile and interpolate all available ground-based and remotely sensed snow water equivalent data [*Liston and Hiemstra*, 2008]. SnowAssim is run prior to regular SnowModel simulations using a scheme that optimizes interpolation by calculating the differences between observed and modeled snow values and retroactively applies multiplicative corrections to melt factors or precipitation values to create improved fields prior to the assimilated observations. SnowModel is then run again using the new precipitation fields as input. This early, automated form of calibration improves simulations of snow distribution throughout the season rather than only at the time of observation, generating more accurate spatial distribution of snow depth and SWE.

For the second calibration stage, we adopt a traditional grid search approach to tuning model parameters, beginning with a broad search across the parameter space then focusing on narrower ranges with a finer grid. For this, we identify which SnowModel-HydroFlow parameters to treat as tuning parameters and which can be prescribed. SnowModel-HydroFlow has an extensive suite of parameters, many of which have been determined from field measurements or from modeling experiments. Based on a review of other SnowModel-HydroFlow studies and focusing on importance to localized meteorological and hydrological conditions in glacierized mountain terrain, we initially select seven parameters: glacier albedo, fresh snow albedo, melting (non-forested) snow albedo, monthly precipitation lapse rates, monthly temperature lapse rates, and factors for modifying each the slow and fast reservoir velocities in the HydroFlow routing module (acting to increase or decrease fluid residence time). Preliminary simulations indicate that model results are relatively insensitive to values of fresh snow albedo and the factor for slow reservoir velocities. We therefore focus our calibration efforts on the remaining five parameters. We identify a range of physically realistic values to test for each, as guided by the literature and other SnowModel studies (Table 2.2). All other SnowModel parameters are set to default SnowModel values, a select list of which is also shown in Table 2.2.

We next establish calibration datasets and appropriate metrics to evaluate model performance. We first prioritize matching our estimated SnowModel glacier mass change and the long-term geodetic estimate from *Berthier et al.* [2018]. We aim to minimize the difference between our model results and that derived by *Berthier et al.* [2018] over the same time period. To do this we define $\dot{B}_{\mathrm{diff}}$ as $|\dot{B}_{\mathrm{mod}}$ - $\dot{B}_{\mathrm{geo}}|$ where $\dot{B}_{\mathrm{mod}}$ is the annually-averaged glacier-wide mass change rate from the model and $\dot{B}_{\mathrm{geo}}$ is -0.68 $\pm$ 0.15 m w.e. a^{-1}. We next compare HydroFlow output of discharge (Q) to streamflow data for the four local drainages, aiming to obtain Nash-Sutcliffe Efficiency (NSE) [*Nash and Sutcliffe*, 1970] nearest to 1. We generate separate statistics for each instrumented basin, but prioritize matching those with the highest percent glacier cover (Mendenhall River, 56%, and Lemon Creek, 46%). Finally, we also compare output to point observations of snow and ice melt from the field, aiming to minimize RMSE and maximize r^2 values. However, after the initial automated calibration step (SnowAssim) that uses SWE observations to determine melt factors, modeled point melt values are relatively insensitive to parameter value change, indicating that the melt factors derived from SnowAssim produce an optimized modeled to observed match.

In summary, we prioritize our performance metrics in the following order: 1) $\dot{B}_{\text{diff}} = |\dot{B}_{\text{mod}}$ - $\dot{B}_{\text{geo}}|$ nearest to 0 for glacier-wide mass balance rates; 2) NSE nearest to 1 for streamflow discharge, prioritizing the statistics for more glacierized basins first; 3) minimizing RMSE and maximizing r^2 statistics for point melt observations. While this focus ensures that we reproduce the glacier component of the overall water balance well, we find that it means sacrificing goodness-of-fit to stream gauge measurements in basins with less glacier cover (Montana Creek, 2%, and Cowee Creek, 11%). We accept this as a cost of striving to correctly characterize glacier volume change and glacier runoff production, which are the focus of our study.

For our final time series analysis, we identify out of our 215 simulations all those that generate glacier mass balance estimates for the full icefield that fall within the error bounds of the $\dot{B}_{\text{geo}}$ goal value for Oct. 1, 2000 to Sept. 30, 2016. This yields an ensemble among which is a midpoint ensemble member that most closely matches the goal value, i.e. with $\dot{B}_{\text{diff}} = 0$, as well as two ensemble end members whose mass balance rates correspond to the upper and lower limit of the *Berthier et al.* [2018] estimate error bars. We use these end members as upper and lower estimates of uncertainty for our midpoint simulation, which we focus on for the bulk of our analyses.

2.4.5 Model validation

To independently validate our model results, we utilize a time series of terrestrial water changes for the Juneau Icefield area derived from the independent data source GRACE.

GRACE gravimetry data On account of their substantial magnitudes, both long-term and seasonal terrestrial mass variations from glacier ice loss and snow loading along the Gulf of Alaska are large enough to alter local gravity fields. The GRACE satellites, whose mission lasted from 2003 to 2016, were tandem satellites that used a microwave K-band inter-satellite ranging system to measure gravity changes of all Earth system components. GRACE pro-

Table 2.2: Calibration parameters for SnowModel-HydroFlow simulations. Note that we also list a selection of prescribed parameters that are not varied.

Parameter	Description and units	Range of values tested	Basis in the literature for tested range	Final value ensemble range and (**best**)
α_{i}	Glacier ice albedo	0.05 to 0.65	0.3 to 0.65 recommended in *Cuffey and Paterson* [2010] for clean to blue ice based on literature; lower limit also extended	0.30 to 0.40 **(0.30)**
α_{smc}	Melting non-forested (clearing) snow albedo	0.15 to 0.70	Although the recommended range for old wet snow is 0.3 to 0.7 in *Cuffey and Paterson* [2010]; we extend the lower limit to account for dust, black carbon [*Nagorski et al.*, 2019] and snow algae [*Ganey et al.*, 2017])	0.40 to 0.50 **(0.50)**
α_{smf}	Melting forested snow albedo	–	Default SnowModel value, and same as *Beamer et al.* [2016], which found model results for the Gulf of Alaska to be relatively insensitive to this value	0.45
α_{sf}	Fresh snow albedo	–	Model results insensitive on initial tests	0.75
$\Gamma_{\mathrm{Jan}}, \Gamma_{\mathrm{Feb}} \ldots$	Monthly varying temperature lapse rates (showing Jan/ June in $^{\circ}$C km^{-1})	2.4/6.2 to 6.4/10.2	We test the SnowModel default seasonal pattern and modify in $\pm$ 0.5°C km^{-1} steps	2.4/6.2 to 4.4/8.2 **(3.9/7.7)**
$\chi_{\mathrm{Jan}}, \chi_{\mathrm{Feb}} \ldots$	Monthly varying precipitation lapse rates (showing Jan/ June in km^{-1})	0.20/0.05 to 0.50/0.35	We test the SnowModel default seasonal pattern and modify in $\pm$ 0.5 km^{-1} steps	0.20/0.05 to 0.35/0.20 **(0.20/0.05)**
$\mathrm{f_f}$	Factor for fast response time; channel flow	0.05 to 2.0	Recommended range in HydroFlow	0.25 (**0.25**)
$\mathrm{f_s}$	Factor for slow response time; matrix flow	–	Model results insensitive on initial tests; value same as *Beamer et al.* [2016]	0.05
$\mathrm{T_{rain}}, \mathrm{T_{snow}}$	Threshold rain/ snow temperatures ($^{\circ}$C)	–	Default SnowModel values, common in modeling studies, e.g. *Young et al.* [2018], *Beamer et al.* [2016]; *Rohrer* [1989]	0/2

cessing involves forward-modeling of gravity signals from glacial isostatic adjustments, Earth tides, ocean tides, and atmospheric loading (i.e. clouds) in order to isolate the remaining signal of interest [*Wouters et al.*, 2014].

To independently validate our model results, we choose GRACE data from NASA Goddard Space Flight Center Geodesy Laboratory's high resolution v2.4 mass concentration (mascon, i.e. grid cell) solution, which provides mass change estimates at ~30-day intervals and 1° x 1° (~12,390 km^2) resolution [*Luthcke et al.*, 2013]. Data are available at https://earth.gsfc.nasa.gov/geo/data/grace-mascons. This solution represents the full terrestrial water budget – i.e. snowfall, rain, and runoff from nonglacierized and glacierized terrain, including glacier ice melt – and is therefore optimized for terrestrial hydrology. We focus on the two GRACE mascons containing the Juneau Icefield (Figure 2.1). We choose this GRACE product because it is one of few that explicitly corrects for local mass increases from post-Little Ice Age disintegration of the Glacier Bay icefield [*Larsen et al.*, 2005], as estimated using the ICE-5G glacial isostatic adjustment model [*Peltier*, 2004]. This GRACE product also compares well with regional-scale mass balance model simulations for the Gulf of Alaska [*Hill et al.*, 2015; *Beamer et al.*, 2016] and to mass loss estimates from NASA's Ice, Cloud, and Land Elevation Satellite (ICESat) [*Arendt et al.*, 2013]. Moreover, this solution is among the first to provide information for constructing 95% confidence intervals on mass changes for individual mascons based on estimates of noise and leakage, as detailed in *Loomis et al.* [2019].

The primary benefit of using GRACE data is the high temporal resolution which provides sub-annual water balance information. Additionally, GRACE provides a direct measurement of mass changes; that is, no density assumptions are required to estimate snow and ice mass loss, which are a large source of uncertainty in other water and glacier mass balance methods. The disadvantage of GRACE is that the fundamental spatial resolution of the v2.4 processing approach is a 300 km Gaussian smoothing filter [*Luthcke et al.*, 2013], resulting in a) coarse resolution, and b) possible signal leakage across mascon boundaries, a processing artifact.

For comparison of our model results to the GRACE time series, our model spatial domain includes all terrain within the two GRACE mascons surrounding the icefield. We extract this spatial domain and select mass change estimates at dates corresponding with the mid-points of the GRACE time series monthly averages. We calculate the long-term mass loss trend by fitting an annual sinusoid to data using a least-squares approximation. Individual annual amplitudes are calculated by subtracting annual minima from maxima, an approach deemed appropriate for the Gulf of Alaska region due to its clean seasonal signal relative to noise [*Luthcke et al.*, 2013].

2.4.6 Water balance, glacier mass balance, and runoff calculations

Using SnowModel-Hydroflow as described above, the water balance for our domain is calculated by:

$$\dot{S} = \dot{P} - \dot{R} - \dot{ET} - \dot{SU} \tag{2.1}$$

where S is the volume of water stored within the seasonal snowpack, glacier ice, or top 1 m of soil; P is precipitation input (rain or snow); R is runoff (defined as the water immediately available for routing to downslope areas); ET is evapotranspiration; and SU is sublimation at the snow surface. Dot notation indicates that all quantities are taken to be rates (time derivatives). Note that because none of the glaciers within the domain are ocean-terminating, we do not include marine iceberg calving or submarine melt within equation (2.1). Although several glaciers are lake-terminating, previous studies on the Mendenhall Glacier (historically land-terminating but now ending in a proglacial lake) revealed that iceberg calving represents only 4 to 6% the amount of ice lost through surface melt [*Boyce et al.*, 2007; *Motyka et al.*, 2002]. Similar to *Ziemen et al.* [2016], we therefore consider ice discharge into lakes to be a small component of Juneau Icefield glacier mass balance, and an even smaller part of water balance of the coastal watershed.

In SnowModel, runoff R is water that is immediately available to be routed downstream, and is the sum of glacier ice melt, snowmelt that does not refreeze or fill pore space within the snowpack, rain on bare surfaces (i.e. rain that does not fall onto snow or soil substrates), or rain on already-saturated snow or soil. We note that the term 'glacier runoff' is used ambiguously within the literature and often represents different physical quantities [*O'Neel et al.*, 2014; *Radić and Hock*, 2014]. For our purposes, we define glacier runoff as all runoff produced over glacierized cells. This formulation is identical to two studies that modeled runoff for the Gulf of Alaska [*Beamer et al.*, 2016; *Neal et al.*, 2010] as well as to the quantity defined conceptually in *O'Neel et al.* [2014] as total runoff from the glacier surface (concept 5). We use the term 'glacier ice melt' separately, to denote meltwater from the glacier surface only after snow cover has been removed (i.e. it is one component of glacier runoff). We calculate both quantities throughout the study.

We calculate the area-averaged glacier mass balance using equation (2.1) over glacierized grid cells only (noting that evapotransporation (ET) goes to zero over glacier surfaces). Glacier mass balance therefore represents a portion of the full spatial domain's water storage S. The contribution of non-glacierized cells makes up the remaining portion.

All comparisons of model output to stream gauge instruments are comparisons to:

$$Q = \dot{R} - \dot{ET} \tag{2.2}$$

i.e. discharge Q (a flux) is all runoff that has been routed to a known gauge location, after evapotransporation ET has been taken into account.

Finally, comparisons of model output to GRACE data are to water storage S, given that the GRACE satellites measure all changes in water mass distribution over Earth's surface.

2.4.7 Trend analyses

We evaluate trends in magnitude and timing of hydrological variables (total runoff, glacier runoff, glacier ice melt, and water balance), integrated over the full spatial domain draining west to the coast. For trends in magnitude, we examine spatially and temporally integrated quantities including annual volumes of total runoff, precipitation, glacier runoff (the sum of ice melt, snowmelt, and rain on the glacier surface), glacier ice melt (i.e. melt at the glacier surface after snow has been removed), and water balance. We also identify maximum and minimum daily values for each year for total runoff, glacier runoff, glacier ice melt, and water balance. Further, we examine volumes of glacier runoff and ice melt for spring and summer seasons, where each season's start and end dates are defined by the maximum, minimum, and inflection points of the domain- and temporally-averaged annual air temperature climatology derived from the MicroMet-interpolated climate input data. Here, 'winter' falls between December 24 to April 6, 'spring' is April 7 to July 17, 'summer' is July 18 to October 11, and 'fall' is October 12 to Dec 23. Finally, we assess cold season volumes of glacier runoff and glacier ice melt. Here, the cold season is defined as the period between late-fall termination and spring onset of glacier runoff and ice melt, which correspond to the latest and earliest dates that respectively follow or precede a period of at least two weeks of glacier runoff/ice melt below a near-zero threshold. This two-week criteria was chosen out of several algorithms for best reproducing manually-selected dates.

For trends in timing, we use the raw complete time series to test for trends in: day of year of minimum daily volumes of total runoff and water balance; day of year of glacier runoff and glacier ice melt onset and end, as well as the length of the season in between; and number of non-zero days of cold season glacier runoff and ice melt. For trends in the timing of peak flows (i.e. maximum daily volumes of total runoff, water balance, glacier runoff, and glacier ice melt) in particular, we test for day of year trends in a time series smoothed with a 14-day running mean in order to capture the overall shape of the hydrograph and minimize the effect of extremes.

Trends are detected using the Mann-Kendall test for significance, a non-parametric test (i.e. data do not have to meet the assumption of normality). Trends are calculated using the Theil-Sen estimator, a non-parametric approach that fits a trend by determining the median of the slopes of lines through each pair of points in a sample. This approach is more robust against outliers than simple linear regression, making it well-suited to, and commonly used in, hydrological applications [*Helsel and Hirsch*, 2002]. To identify the statistical significance of each trend, we report a harmonic mean p-value, a formulation for combining p-values from tests that cannot be guaranteed to be independent [*Wilson*, 2019], e.g. model simulations with the same input data and physics but variation in parameter values. We calculate a harmonic mean p-value for every trend by equally weighing our midpoint and two end member simulation p-values.

In reporting our findings, we take an approach that extends beyond the traditional method of judging results as meaningful solely by the p-value ≤ 0.05 criteria. This has been challenged in recent years, citing limitations such as variation in p-value statistics across replicate studies [*Halsey et al.*, 2015] and difficulty in interpreting results when the p-value is high and the null hypothesis cannot be rejected [*Cohen*, 2016]. We turn instead to recommendations from *Halsey* [2019] and *Tomczak and Tomczak* [2014] to include a measure of effect size (which in our case is the trend itself) as well as 95% confidence intervals surrounding each trend, in order to provide additional insight into the range of possibilities that are reasonably likely. We also heed advice from *Amrhein et al.* [2019] that including factors such as background evidence, data quality, and understanding of underlying mechanisms can contribute to meaningful interpretation of statistical results. As such, we include as an interpretive tool for the reader a qualitative assessment of our confidence that a positive trend should be detected, in the context of our full suite of results and a priori current knowledge from the literature for each climatological and hydrological variable.

2.5 Model initialization and calibration

In this section, we describe outcomes from the initialization and calibration process, from which we are better able to understand the strengths and limitations of our model results.

To assess the performance of the MicroMet meteorological interpolation module, we compare daily MicroMet-interpolated MERRA-2 air temperature fields to observations from National Oceanic and Atmospheric Administration (NOAA) airport weather stations at Juneau and Skagway (Figure 2.1), and find strong correlation ($r^2 = 0.92$ and 0.88, respectively). However, we find systematic biases between modeled and observed temperatures, when averaged monthly, with lower than observed temperatures in winter months (as large as of -2.1°C in Juneau and -5.5°C in Skagway) and higher than observed temperatures in summer months (as large as 2.0°C in Juneau and 2.8°C in Skagway). In terms of daily precipitation, modeled and observed volumes were weakly correlated in both Juneau ($r^2 = 0.52$) and Skagway ($r^2 = 0.40$). Mean monthly modeled fields also overproduced precipitation, particularly in fall and early winter months, with biases between 1.3 and 4.7 mm w.e. d^{-1} for Juneau and 0.8 to 2.3 mm w.e. d^{-1} for Skagway. Note that we did not apply a monthly bias correction to the model fields for temperature or precipitation because both weather stations used for comparison are biased to low elevations, and we have no additional information for spatially distributing a correction across the large distance and complex topography between the airports. We assume, therefore, that these biases are accommodated for by adjustment to the tuning parameter suite.

We evaluate the impact of our initial calibration routine SnowAssim by comparing SnowModel on-glacier point SWE estimates to observations from glacier mass balance field and airborne campaigns (Figure 2.2). We observe that model reproduction improved markedly from $r^2 = 0.45$ to $r^2 = 0.90$ and RMSE = 0.45 m w.e. to RMSE = 0.18 m w.e (Figure 2.2). This highlights that the SnowAssim routine produces more realistic SWE fields irrespective of location or duration between observations. The model also reproduces independent point melt (i.e. snow/ice ablation) observations, with $r^2 = 0.79$ and RMSE = 1.63 m w.e (Figure 2.3). The larger RMSE values are not unexpected given the predominance of ablation measurements at lower elevations in the ablation area (60% of the observations are at < 800 m a.s.l.), which on large glaciers with undulating surface topography often display substantial local variability that may not be well-captured by the model (e.g. *Young et al.* [2018]). However, we note that the model appears to underpredict melt for more negative point mass

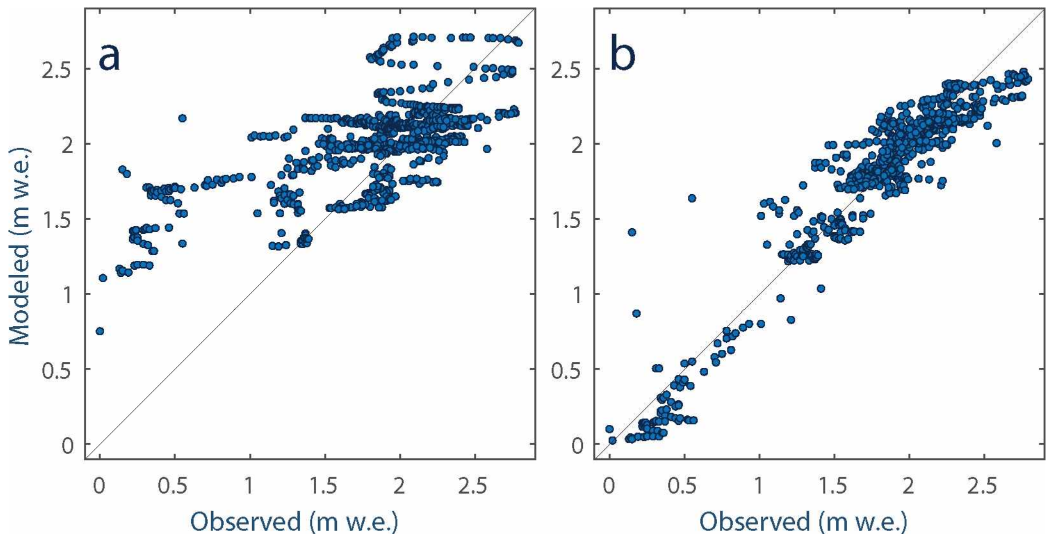

Figure 2.2: Comparison of observed versus modeled snow water equivalent (SWE) values at on-glacier locations both a) before, and b) after the application of the SnowAssim initial calibration routine. Results are shown for the ensemble member driven with the best fit parameters; other ensemble members are similar.

balances, which may be due to the above-mentioned lower-than-observed temperatures in the summer months.

In the second calibration phase, we succeed in tuning parameters to reproduce the geodetic mass balance rate from *Berthier et al.* [2018], -0.68 $\pm$ 0.15 m w.e. a^{-1} for 2000 to 2016. From the ensemble of all simulations that meet this criteria, we focus our primary analysis on the midpoint simulation with a mass balance rate of exactly -0.68 m w.e. a^{-1}, and consider the ensemble end members – whose mass balance rates are nearest the upper and lower error bounds from *Berthier et al.* [2018] – to be the limits of our uncertainty. Best-fit parameter values are shown in Table 2.2. This step of calibrating to a long-term mass balance rate is crucial for correctly characterizing glacio-hydrological systems. Had we not undertaken this step, our initial simulations using SnowModel default parameter values would have yielded a mass balance rate of +0.08 m w.e. a^{-1}.

Our ability to reproduce observations from stream gauge records on the four instrumented basins varies by the amount of glacier cover (see Figure 2.4). For the two glacierized basins with the largest percent cover, comparison of modeled to observed monthly discharge yields

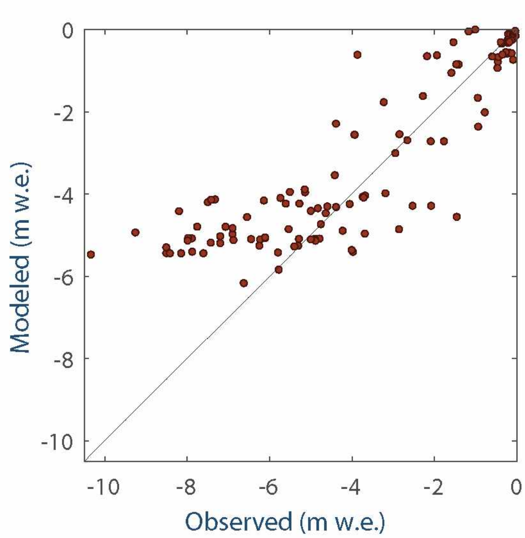

Figure 2.3: Comparison of observed versus modeled point snow/ice ablation values at on-glacier locations, as driven with the best fit parameters.

stronger agreement: for Mendenhall River (56% glacier cover), we obtain NSE = 0.84 and $r^2 = 0.88$, and for Lemon Creek (46% glacier cover), we find NSE = 0.76 and $r^2 = 0.82$. The model, however, is unable to reproduce many of the large peaks in the daily Mendenhall discharge record, several of which are associated with recent (2011 and on) glacier lake outburst floods from an upstream tributary basin. The model does not include a mechanism to generate these impulsive events. For the two basins that are predominantly forested, modeled to observed agreement is weaker: for Montana Creek (2% glacier cover), we find NSE = -1.37 and $r^2 = 0.45$, and for Cowee Creek (11% glacier cover), we obtain NSE = -0.81 and $r^2 = 0.47$. We also note that the Mendenhall River and Lemon Creek watersheds show evidence of seasonal biases between modeled and observed quantities, with the model generally over-producing runoff in summer and under-producing in fall. We discuss this, and provide possible reasons for the modeled-to-observed discrepancy in less-glacierized basins, in Section 2.7.1. Altogether, weighing all four basins according to both above-gauge basin area as well as length of observational record, we calculate a weighted NSE = 0.21 and weighted $r^2 = 0.73$. We believe this performance to be acceptable given that, rather than any one process in isolation, streamflow represents an integration of all glacio-hydrological processes in the watershed, and thereby has the potential to integrate any sources of error with input data as well as model physics into a single metric. Because our model performs well in reproducing other calibration datasets, particularly in glacierized watersheds (e.g. our estimate for the 2000 to 2016 mass balance rate for the Mendenhall Glacier alone is -0.73 m w.e. a^{-1}, which matches the estimate of -0.73 $\pm$ 0.13 m w.e. a^{-1} from *Berthier et al.* [2018]), we are confident in the calibrated model performance.

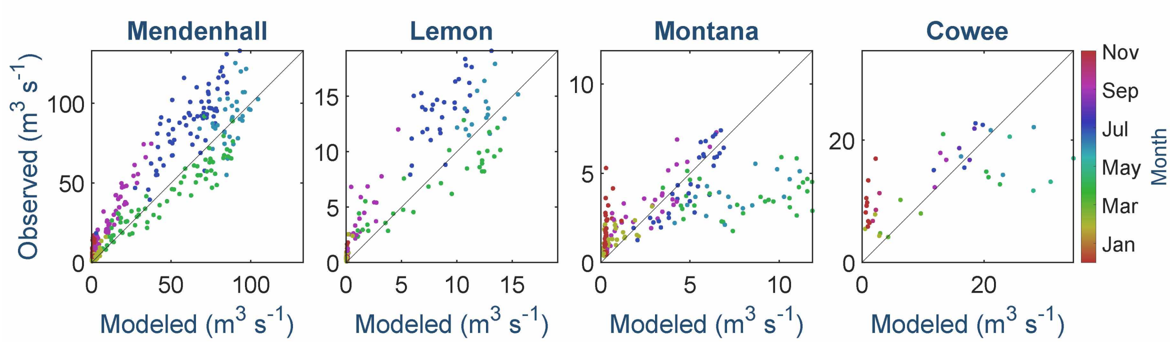

Figure 2.4: Mean monthly discharge Q from observations versus model results for four instrumented watersheds in cubic meters per second, as driven with the best fit parameters. Note the differing axis scales.

2.6 Results

2.6.1 Glacier mass balance

Our modeled, tuned annual glacier-wide mass balance rate for the Juneau Icefield is -0.68 m w.e. a^{-1} for 2000 to 2016, with lower and upper uncertainty bounds of -0.57 and -0.83 m w.e. a^{-1} corresponding to our simulation ensemble end members. Extending to the full model period of Oct. 1, 1980 to Sept. 30, 2016, we calculate a rate of -0.57 [-0.11, +0.12] m w.e. a^{-1} for the icefield, suggesting an acceleration in recent decades. Finally, for all ice contained within the domain draining to the coast, our model estimates a mass balance rate of -0.81 [-0.08, +0.11] m w.e. a^{-1} for 1980 to 2016, suggesting that the ice nearest the coast (i.e. to the west of the topographic divide) experiences greater rates of mass loss than the more interior glaciers. Cumulative glacier-wide specific mass balance for the full model period is shown in Figure 2.5. Annual glacier mass balance over this time period and domain is comprised of, on average, 3.07 ± 0.01 m w.e. a^{-1} of precipitation, 3.85 [-0.08, +0.10] m w.e. a^{-1} of glacier runoff, and 0.03 ± 0.01 m w.e. a^{-1} of sublimation from the snow surface.

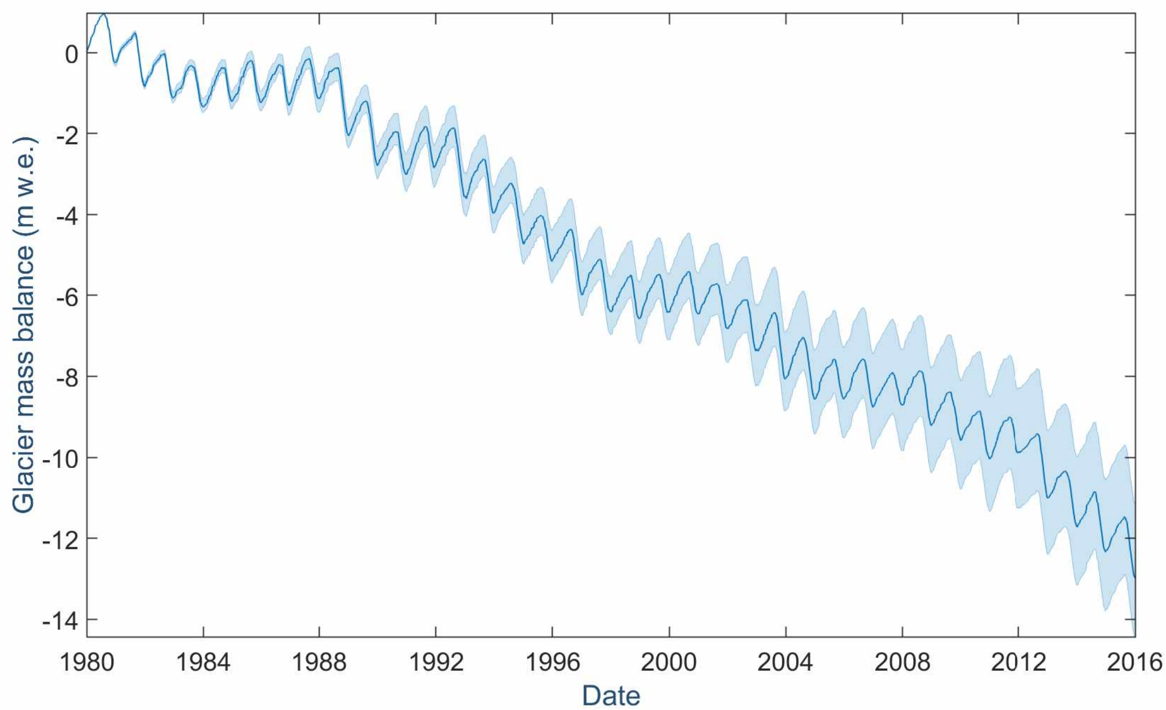

Figure 2.5: Modeled cumulative glacier-wide specific mass balance for the full model period of Oct. 1, 1980 to Sept. 30, 2016 for all coastal ice of the Juneau Icefield. The upper and lower limits of uncertainty correspond to the model ensemble end members, whose trends correspond to the upper and lower limits of uncertainty of the calibrating geodetic mass balance estimate for 2000 to 2016 from [*Berthier et al.*, 2018].

2.6.2 Freshwater runoff

For the watershed encompassing all Juneau Icefield glacier ice draining to the coast, we estimate mean annual freshwater runoff of 20.0 [+0.5, -0.4] km^3 a^{-1} for 1980 to 2016. Of this, 11.0 ± 0.3 km^3 a^{-1} (or 55 ± 1%) is glacier runoff (i.e. runoff sourced from the glacier surface). The water balance volume we calculate is, on average, -2.1 [+0.4, -0.3] km^3 a^{-1}, though as we discuss below in Section 2.7.1 this is believed to be an underestimate of the long-term water storage loss. For ice-only cells, we calculate water storage losses (i.e. glacier volume loss) of 2.4 [-0.3, +0.2] km^3 a^{-1} for the same time period, which means that glacier volume loss (the percentage of runoff due to the persistent negative mass balance trend, rather than seasonal magnitudes of glacier runoff) comprises 12 ± 1% of total runoff in the domain and 22 [+1.0, -1.4] % of glacier runoff. Precipitation over the full domain delivers an average of 18.3 km^3 a^{-1}, while evapotranspiration and sublimation from the snow surface are small, at 0.17 [-0.07, +0.02] km^3 a^{-1} and 0.17 [-0.07, +0.02] km^3 a^{-1}. Mean monthly values of each of these variables are shown in Figure 2.6, though evapotranspiration and sublimation are not visible at this scale.

To better understand the linkages between individual water balance components, we assess the correlation between different modeled quantities. We find that annual volumes of glacier runoff and total runoff for the domain are highly correlated ($r^2 = 0.90$, $p < 0.001$), while glacier runoff and glacier ice melt are less so ($r^2 = 0.68$, $p < 0.001$). Glacier ice melt is also weakly correlated with total runoff ($r^2 = 0.45$, $p < 0.001$).

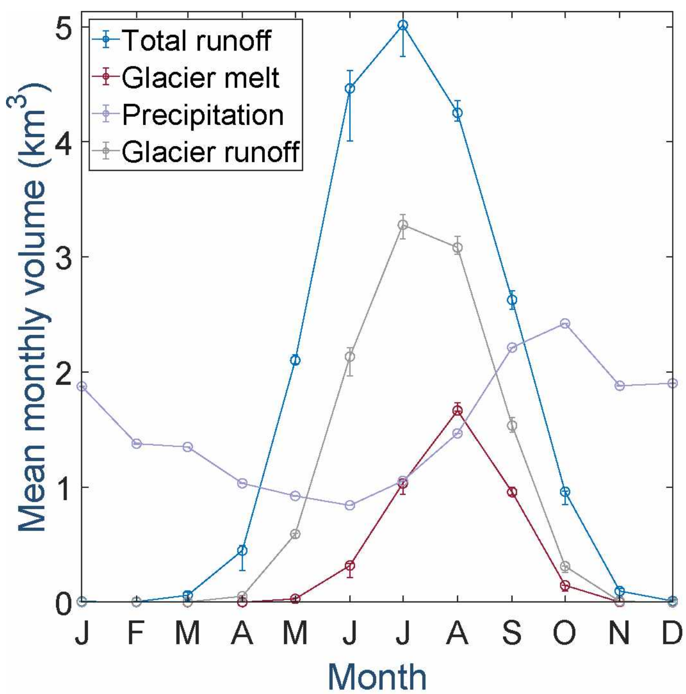

Figure 2.6: Mean monthly volumes of total runoff, glacier runoff, glacier ice melt, and precipitation for the full 1980 to 2016 period. Note that evapotranspiration and sublimation, though included within our model calculations, are very small and not shown.

2.6.3 Water balance and comparison with GRACE

For the 2003 to 2016 period overlapping with GRACE data availability, we calculate a glacier-wide mass balance rate for all ice in the GRACE two-mascon domain of -0.51 [-0.18, +0.13] m w.e. a^{-1} (or -2.5 [-0.9, +0.6] km^3 a^{-1}), in close agreement with the GRACE-derived negative trend estimate of -0.55 m w.e. a^{-1} (-2.7 km^3 a^{-1}), as shown in Figure 2.7a. Correlation between these two time series is robust, with $r^2 = 0.91$ and $p < 0.001$ (Figure 2.7b). These results showcase the model's ability to reproduce the climatic conditions over the ice-covered portions of the domain that are driving sub- and interannual water storage changes.

However, in comparing GRACE to modeled results for ice and land cells together, we observe that correlation is less strong ($r^2 = 0.36$, $p < 0.001$). This discrepancy can be seen in the SnowModel land+ice time series in Figure 2.7a primarily as a lack of agreement in the overall trend, which is not sufficiently negative at -0.002 m w.e. a^{-1}. We discuss this further in Section 2.7.1. Nonetheless, our full SnowModel land+ice water balance produces seasonal amplitudes (mean annual accumulation = 25.8 km^3 a^{-1}, ablation = -26.6 km^3 a^{-1}) that are more in line with those from GRACE (18.1 and -21.5 km^3 a^{-1}) than those from ice cells alone (9.0 and -12.1 km^3 a^{-1}). This result is encouraging as, again, the GRACE solution we use measures all components of the terrestrial water balance.

2.6.4 Trends in magnitude and timing

We next assess trends in the timing and magnitude of different hydrological variables, and summarize results of trend detection tests in Table 2.3. In the spirit of reports from the International Panel on Climate Change (e.g. *Masson-Delmotte et al.* [2018]), we also include as an interpretive guide a column with a qualitative assessment of our confidence that a positive trend should indeed be present in each specific variable, given the trend result in context with our full suite of results as well as a priori information.

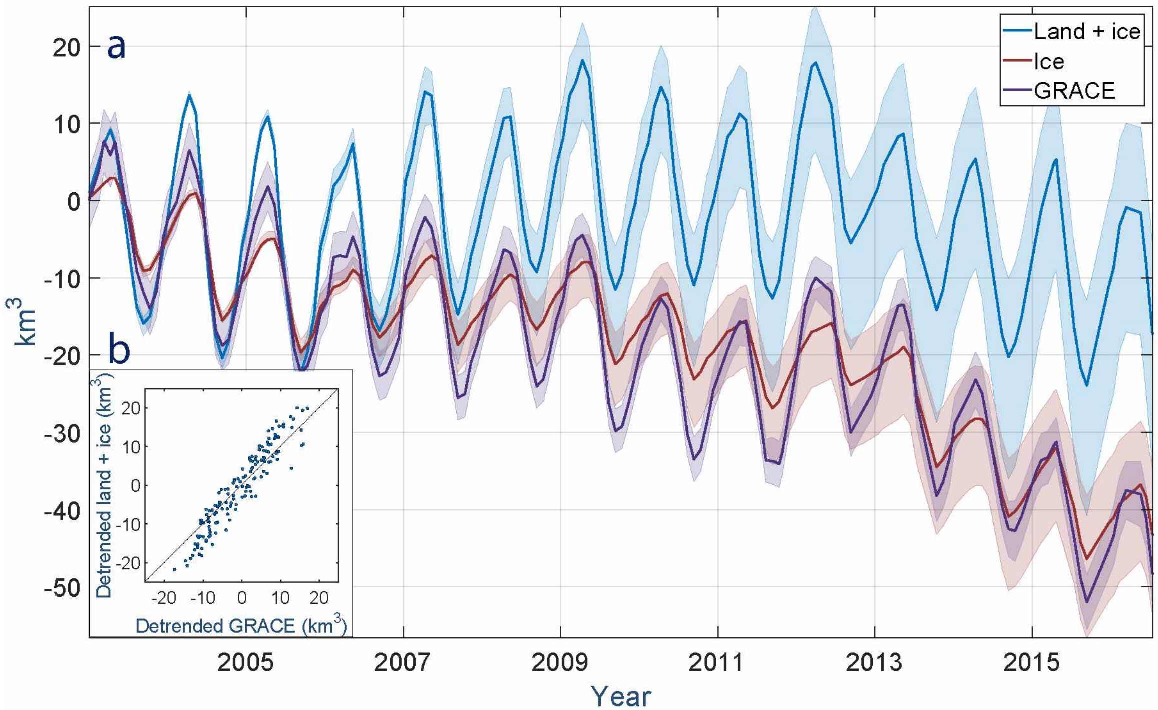

Figure 2.7: Time series and scatter plot of water balance from GRACE and model for 2003 to 2016. a) Water balance time series comparing the GRACE two-mascon domain (purple) with that derived from SnowModel with land+ice cells together (blue) and ice cells only (red). b) Scatter plot comparison of detrended modeled land+ice water balance values versus equivalent from GRACE.

To help interpret our model output results, we first assess trends in the principal input variables of precipitation and mean air temperature. We find no reliable trend in annual precipitation volume, but do find an increase in mean air temperature (0.1°C decade^{-1}), which is consistent with recent analyses of air temperature trends in Alaska, including *Bieniek et al.* [2014] who found a 0.2°C increase in the northern portion of the Juneau Icefield between 1980 to 2012.

Of all variables tested, the most statistically robust ($p \leq 0.05$) trends are related to shifts in timing of the peaks of the 14-day smoothed glacier ice melt curve (occurring 2.5 days earlier per decade) and glacier runoff curve (occurring 4.4 days later per decade) (Figure 2.8). The day of year of the water balance minimum is also found to be occurring 3.5 days earlier per decade.

From a seasonal perspective, the most statistically robust trends with the largest effect sizes occur in our hydrological variables in the spring season (Figure 2.9). We also observe an increase in glacier ice melt in summer.

Among the different hydrological variables examined, the most robust trends are related to glacier ice melt. These include the volume of spring glacier ice melt (increasing by 16.5% decade^{-1}) and, with slightly less statistical strength, the annual volume of glacier ice melt (9.6% decade^{-1}), both of which are visible in Figure 2.10. Our results also suggest an increase in the magnitude of the maximum daily volume of glacier ice melt (10.2% decade^{-1}).

The large degree of interannual variability in precipitation in this domain increasingly acts to obscure trend detection as the proportion of non-glacier ice grid cells grows in a particular hydrological variable (Figure 2.10). In other words, when examining volumes, we observe the pattern that trends for glacier ice melt, glacier runoff, and total runoff exhibit respectively smaller proportion change with less robust statistical significance. For example, in spring months, we calculate p-values of 0.05, 0.11, and 0.25, and respective trends of 16.5, 6.8, and 2.7% per decade for those three variables. This pattern holds true for each spring, summer (not shown in table), and annual periods, and disappears during fall and winter months when glacier ice melt ceases almost entirely.

Finally, our results also suggest trends for variables associated with colder months, including an increase in the number of days of non-zero glacier runoff during the cold season (2.4 days decade^{-1}), but a decrease in the volume of glacier runoff during winter months (-5.8% decade^{-1}).

To visualize some of these changes spatially, Figure 2.11 shows both the mean annual spatial distributions of freshwater variables for 1980 to 2016 throughout the coastal domain, as well as anomalies from these mean values for the years 1980 to 1990 and 2010 to 2016. These panels demonstrate a significant shift in spatially distributed volumes of freshwater from the beginning and end periods of our model interval.

Of the remaining variables tested, none show trends we believe to be reliable according to our methods, although some may prove to be significant in future years. Of these, fall season volumes show the lowest p-values of any season for all hydrological variables, followed by the winter season. Maximum and minimum daily volumes do not exhibit changes in either volume or timing. Volumes of cold season glacier ice melt and glacier runoff do not appear to have changed substantially over the period of study, nor does the frequency of cold season glacier ice melt events. Finally, we do not detect reliable trends in the onset and end of glacier ice melt or glacier runoff, nor in the length of the melt season in between, although future analyses may reveal changes to these.

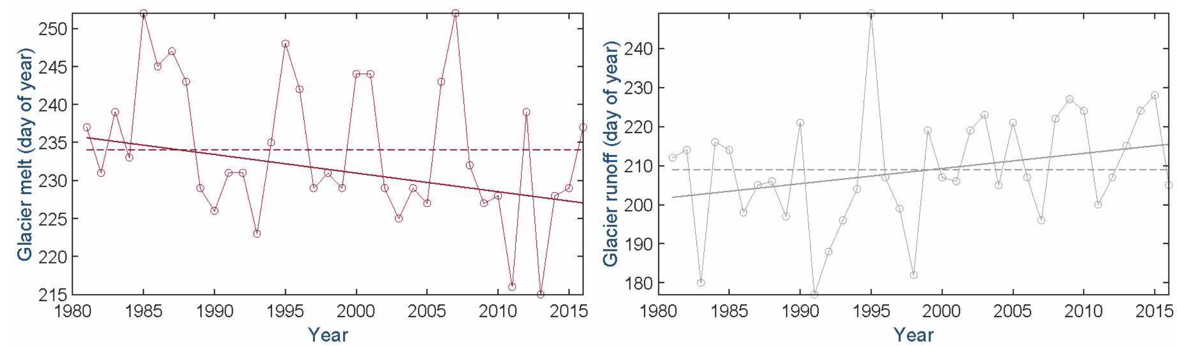

Figure 2.8: Timing of smoothed annual peak of glacier ice melt and glacier runoff in coastal domain. Each panel shows the time series (circles), mean (dotted line), and trend (solid line).

2.7 Discussion

2.7.1 Model performance

Overall, our model calibration approach achieves robust agreement with calibrating datasets of snow water equivalent point mass balance, long-term geodetic glacier-wide mass balance, snow and ice melt point mass balance, and discharge in highly glacierized basins. These results highlight our ability to effectively combine the suite of different physically-based sub-models needed to reproduce accumulation, ablation, and hydrological processes in these complex, glacierized basins.

Table 2.3: Results of trend detection tests for select hydrological variables for all terrain draining west from the Juneau Icefield to the coast. Here all variables are defined as positive (e.g. glacier ice melt is positive even though it represents a loss), such that positive/negative trends correspond to increasing/decreasing quantities in all cases. p-values are given by the harmonic mean of individual Mann-Kendall tests for the midpoint, upper, and lower end member simulations, and **bold** indicates the trends that are statistically strongest. Trends are given by the Theil-Sen slope and a 95% confidence interval is provided for each. The percent change per decade is indicated for the mean trend (column 3) relative to the 1980 to 1989 period. Finally, the last column shows our qualitative assessment of confidence that a positive trend should be present, given our results and in context with the literature (VC = very confident, C = confident, SC = somewhat confident, NC = not confident).

Variable	p-value	Trend and units (a^{-1})	95% confidence interval	% change $(\text{decade})^{-1}$	Trend confidence
Input variables:					
Mean annual air temperature	0.27	0.01°C	[0.00, 0.06]	–	VC
Annual precipitation volume	0.75	-1.7e7 m^3	[-1.2e8, 5.5e7]	-0.9	NC
Mean spring air temperature	0.19	0.03°C	[0.02, 0.09]	–	VC
Spring precipitation volume	0.87	-2.2e6 m^3	[-2.9e7, 1.9e7]	-0.7	NC
Winter precipitation volume	0.10	-3.3e7 m^3	[-2.1e7, 1.9e7]	-1.3	NC
Model output:					
Annual runoff volume	0.48	2.8e7 m^3	[-2.0e7, 1.4e8]	1.4	SC
Annual glacier runoff volume	0.23	3.1e7 m^3	[8.1e6, 1.3e8]	3.0	C
Annual glacier ice melt volume	0.14	3.6e7 m^3	[2.0e7, 1.2e8]	9.6	VC
Spring runoff volume	0.25	2.5e7 m^3	[4.6e6, 8.8e7]	2.7	C
Spring glacier runoff volume	0.11	2.7e7 m^3	[1.8e7, 8.8e7]	6.8	VC
Spring glacier ice melt volume	**0.05**	1.0e7 m^3	[1.0e7, 3.2e7]	16.5	VC
Summer glacier ice melt volume	0.18	2.5e7 m^3	[8.2e6, 8.3e7]	1.8	C
Winter glacier runoff volume	0.16	-4.9e4 m^3	[-2.0e5, -4.8e4]	-5.8	SC
Max daily glacier ice melt	0.12	2.0e3 m^3	[1.6e3, 6.7e3]	10.2	C
DOY of min water balance	0.09	-0.35 days	[-1.2, -0.26]	–	VC
No. of cold season glacier runoff days	0.19	0.24 days	[0.20, 0.86]	25.8	C
DOY of smoothed glacier runoff peak	**0.05**	0.44 days	[0.39, 1.29]	–	C
DOY of smoothed glacier ice melt peak	**0.04**	-0.25 days	[-0.78, -0.25]	–	VC

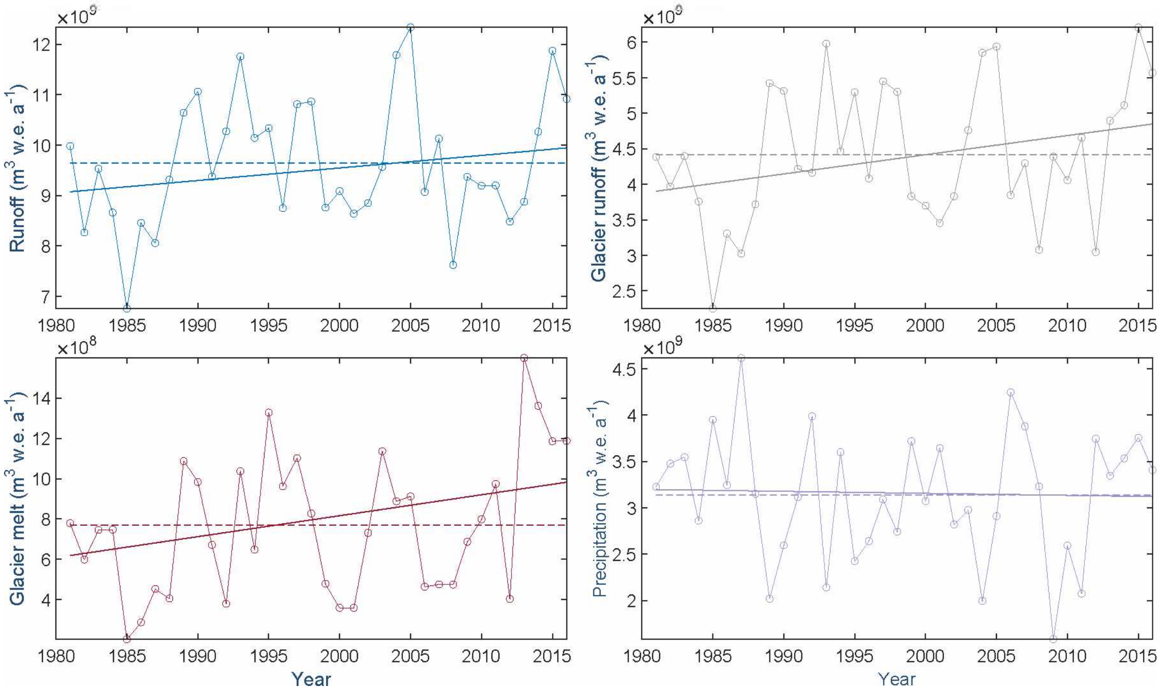

Figure 2.9: Total runoff, glacier runoff, water balance, and glacier ice melt volumes for spring season in the coastal domain. Each panel shows the time series (circles), mean (dotted line), and trend (solid line).

Parameter tuning – system dominated by ice and snow albedo Glacier ice albedo and melting snow albedo in clearings (i.e. non-forested areas, including over glaciers) prove to be the most important parameters for correctly reproducing glacier mass balance rates on par with those from *Berthier et al.* [2018]. We tune both parameters to values on the low end of typical ranges seen in the literature (i.e. 0.30 to 0.40 for glacier ice albedo and 0.40 to 0.50 for melting snow albedo in clearings). The lower values may be explained by the presence of both snow algae (documented on another coastal icefield in Alaska in *Ganey et al.* [2017], and observed by the first author in the field) as well as dust and black carbon [*Nagorski et al.*, 2019]. Both of these light absorbing impurities contribute to an amplifying feedback process by lowering albedo and increasing melt rates, which in turn consolidates material on the snow surface and further increases melt rates. *Nagorski et al.* [2019] confirm through measurement that dust and black carbon density at the surface increases later in the melt season, suggesting that snowpack 'aging' should be taken into

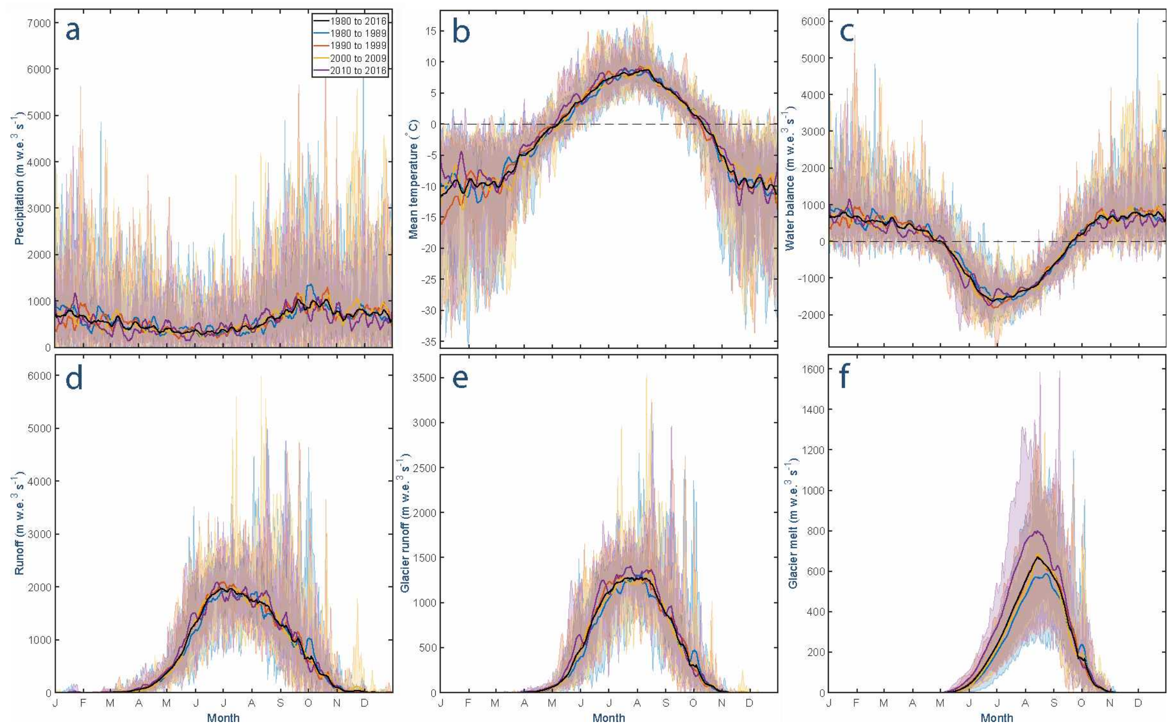

Figure 2.10: Stacked graphs of modeled output of a) precipitation, b) air temperature, c) water balance, d) total runoff, e) glacier runoff, and f) glacier ice melt for the coastal domain, plotted by decade. Solid colored lines represent the daily mean output for each decade, while shaded regions in matching colors represent the corresponding daily range for all years within the given decade. The solid black line shows the 1980 to 2016 mean.

consideration in future melt modeling efforts. Incorporating this process by allowing for monthly-varying albedo values would likely improve our SnowModel-HydroFlow simulations of late-summer freshwater discharge by increasing glacier ice melt and snowmelt during those months. Modeled glacier mass balance rates were insensitive to the value of fresh/dry snow albedo, consistent with the fact that the coastal Juneau Icefield is dominated by aged or wet snow during the runoff season.

We find that within the tested range of precipitation lapse rates, those that were the smallest performed best. This may be explained physically at the scale of the full icefield by any increase in precipitation with elevation being largely canceled out by decreasing precipitation with distance from the coast. This is consistent with findings in *Roth et al.* [2018] who, on examining a cross-sectional path across the icefield along the dominant wind direction,

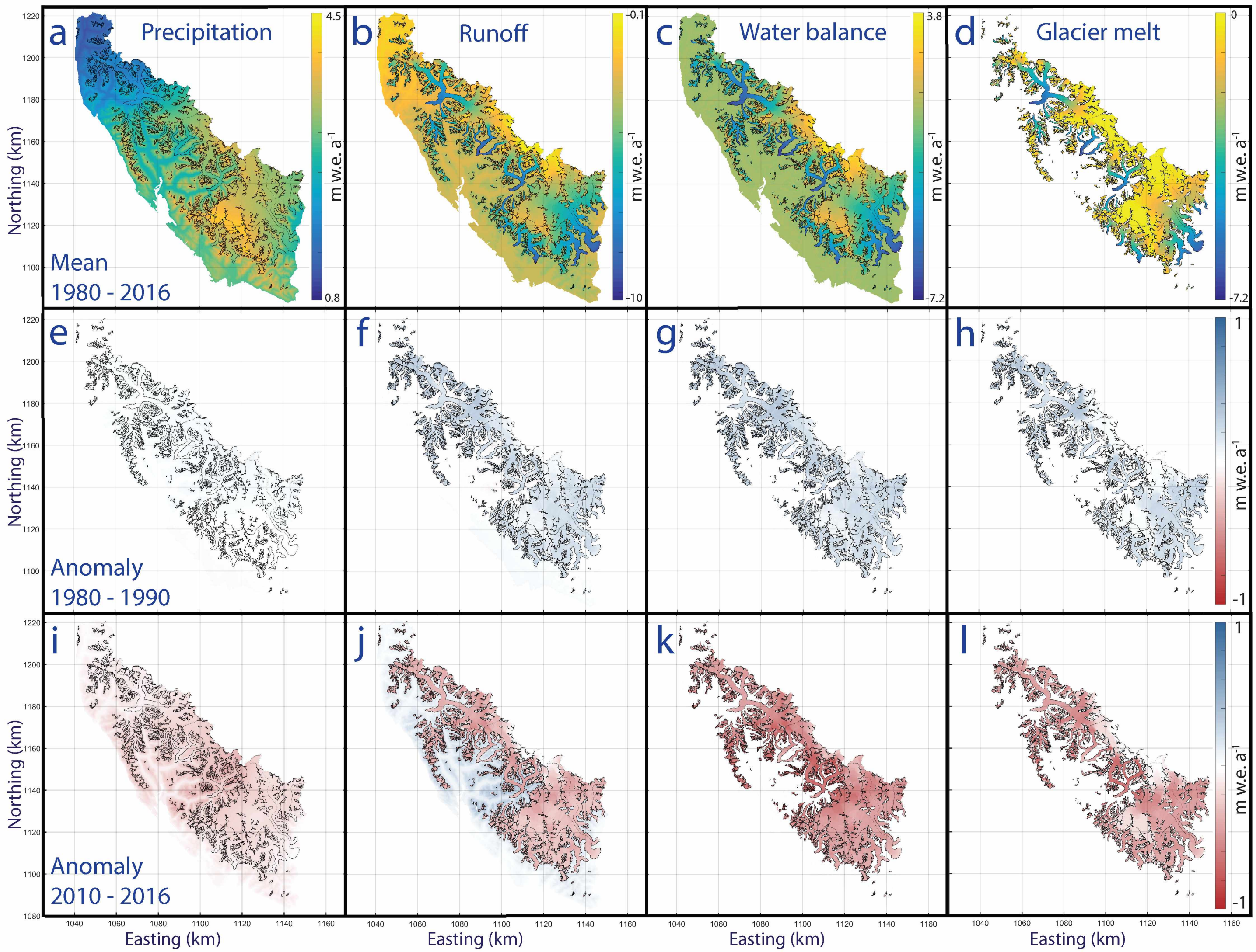

Figure 2.11: Spatially distributed plots of mean 1980 to 2016 annual rates of precipitation, total runoff, water balance, and glacier ice melt, and anomalies from mean for 1980-1990 and 2010-2016. Plots display mean annual rates of precipitation (first column; a, e, and i), total runoff (second column; b, f, and j), water balance (third column; c, g, and k), and glacier ice melt (fourth column; d, h, and l). Figures a-d (first row) display 1980 to 2016 means; note that the scale bars are different for each quantity. Figures e-h (second row) show mean annual anomalies from the 1980 to 2016 mean for the decade 1980 to 1990, while Figures i-l (third row) show anomalies for 2010 to 2016. Figures e-l are displayed using the same color scale. Note that total runoff and glacier ice melt are displayed such that red shading indicates a greater (i.e. more negative) volume than the 1980 to 2016 mean.

found that precipitation increases strongly over the first ∼15 km of the transect in tandem with steep topographical gains, followed by a gradual decrease over the remaining ∼85 km. As SnowModel only applies a single lapse rate over the entire domain, we effectively combine these two effects into a small value. This pattern in precipitation lapse rates may be equally important in other coastal regions with extreme topography rising steeply from sea level and lying along a strong coastal-to-continental gradient. We also find that normal to shallow temperature lapse rates perform the best overall, in agreement with well-established findings that glaciers can impose a dampening effect on local atmospheric lapse rates [*Gardner et al.*, 2009].

Our hydrological simulations reveal that model discharge results are relatively insensitive to the slow reservoir velocity parameter, indicating that most runoff is routed through creeks and streams or over fast-flow terrain such as glacier ice and bare rock. This is supported by the shallow soil reference depth cited in the Harmonized World Soil Dataset [*Fischer et al.*, 2008], and by the modest fraction of forest coverage within the model domain (17% forest, 14% shrubland/grasses/meadows).

Challenges with reproducing stream gauge records While our model adequately reproduces gauge observations in the two basins with high percent glacier cover ($\geq 45\%$), gauge-matching results in the two lesser glacierized basins ($\leq 15\%$) are weaker. This mismatch is evident as an overproduction of discharge in spring, an underproduction in summer, and an underproduction in winter (see Figure 2.4). These patterns are similar in the more glacierized basins, but to a lesser extent. Spring and summer discharge discrepancies may be explained by our finding that MicroMet-interpolated MERRA-2 air temperature fields are generally higher in spring and lower in summer compared to observations, and may therefore generate too much early snowmelt in spring, and too little glacier ice melt in summer. We note that this is consistent with a comparative study of reanalysis products for hydrological applications by *Wrzesien et al.* [2019]. These authors find that in North America, MERRA-

2 does not maintain snow in mountainous terrain for long enough into spring, which they hypothesized may be due to precipitation biases and warm temperatures. We speculate that these effects may appear stronger in the less glacierized basins given the dominance of snowmelt in spring, with little glacier ice melt contribution in spring or summer.

During winter months, modeled discharge in the less-glacierized basins is near-zero, in contrast to observations that show sporadic discharge. However, modeled precipitation volumes in fall and early winter exceed station observations. A possible explanation for the winter month discharge discrepancy is that because our modeled temperatures are lower than observed during winter months, precipitation events arrive as snow instead of rain, thus adding to the snowpack rather than to discharge. Interestingly, this finding is in contrast to *Wrzesien et al.* [2019], who found that MERRA-2 underestimates mountainous snow. However, their spatial domain encompassed large continental watersheds rather than maritime climates. As few other hydrological studies to date have utilized the MERRA-2 product, we hope our findings may increase understanding of its limitations and utility in maritime climates. We note that MERRA-2 relies partly on assimilated station data and partly on model physics to produce precipitation fields for latitudes up to 62.5° [*Bosilovich et al.*, 2015], and that station data are scarce in this region, particularly at elevation. We underscore the critical need for continuous high-elevation stations in the mountainous regions of Alaska for improving both climatological and hydrological models.

In addition to potential MERRA-2 issues, there are also limitations to downscaling coarse-scale meteorological forcing over complex mountain terrain. For example, the MicroMet module does not account for orographic effects (i.e. decreased precipitation on leeward slopes), relying instead on a simple elevation-dependent precipitation adjustment factor. Altogether, there is much room for improvement in the characterization of precipitation and particularly snow in complex mountain terrain with sparse observation networks. In the meantime, our model's limited ability to reproduce discharge in less-glacierized basins may lead to increased uncertainty in the magnitudes of spring and winter runoff in those basins in particular. Given our principal goal of examining changes for a 44% glacier covered domain, with an emphasis on glacier changes, we accept this cost.

Agreement with GRACE highlights reproduction of large-scale climate processes

The robust agreement between the model and GRACE (Figure 2.7), in terms of both long-term trends and time series correlation, emphasizes the model's ability to reproduce meso- and synoptic scale climatic processes driving sub- and interannual water balance changes over glacierized terrain. We note that the mass balance rate we derive for the larger GRACE domain (-0.51 [-0.18, +0.13] m w.e. a^{-1}) is less negative than that for only the Juneau Icefield for the same time period (-0.71 m w.e. a^{-1}). We attribute this to inclusion in the GRACE domain of many smaller, higher-elevation glaciers with less negative mass balance rates even at their termini (~-2 m w.e. a^{-1}) relative to the large, low-elevation valley glaciers that dominate the icefield (~-8 m w.e. a^{-1}).

Our finding that modeled seasonal amplitudes for the full land+ice domain are a closer match to those from GRACE than those from the ice-only terrain is consistent with findings for the Gulf of Alaska in *Beamer et al.* [2016] and the Canadian Arctic Archipelago in *Lenaerts et al.* [2013]. In both studies, seasonal amplitudes from GRACE solutions could only be reproduced by summing together model-generated mass changes over both glacierized and ice-free regions of their modeling domains. In earlier generations of GRACE products, GFSC attempted to isolate from the GRACE solution not the full terrestrial water balance but rather the glacier mass change signal alone, with non-ice terrestrial water storage (TWS) changes removed. However, those land-based variations were sourced from a coarse resolution product from the Global Land Data Assimilation System (GLDAS)/Noah dataset of land surface states and fluxes, available at 0.25 x 0.25° [*Rodell et al.*, 2004], and in which variations are set to zero over glaciers. This coarse spatial resolution means that TWS variations from GLDAS/Noah for heavily glacierized regions like the Gulf of Alaska are minimal, and that earlier GRACE solutions for the region therefore inherently contained both glacier and TWS signals. Our simulations confirm this, given that the seasonal amplitudes of the GRACE solution are only achieved by summing together water mass changes over both glacierized and ice-free areas (Figure 2.7). This result emphasizes the potential for regional scale hydrological modeling to inform our understanding of GRACE.

In terms of long-term trends for the full water balance, our model results show a less negative trend than is estimated using GRACE. This discrepancy is also evident in results using MERRA-1 in *Beamer et al.* [2016], who applied SnowModel at coarser (1 km) resolution over the full Gulf of Alaska region. However, using their best-performing climate product (Climate Forecast System Reanalysis), those authors found favorable agreement between trends. This is a result they believe shows that what has to date been interpreted within GRACE as the long-term ice loss trend is correctly attributed (i.e. that none or little of the trend is attributable to TWS). This interpretation is also consistent with a study by *Reager et al.* [2016], which used reconciled glacier mass balance estimates to isolate global TWS changes from GRACE, and found little in the way of a TWS trend along the Gulf of Alaska. These two regional studies suggest that the increasing trend we see over ice-free land in our model results is likely incorrect, particularly because the model does not account for real storage-enhancing processes (e.g. aquifer recharge, uptake into vegetation in newly deglaciated terrain) that would counteract the expected decreasing water balance from glacier ice loss. One possible explanation for the increase may be due to biases within our MicroMet-interpolated MERRA-2 input data, which may produce more precipitation over cells in our domain that is not contributing to runoff. In particular, the model is likely generating excess, perennial snow over high elevation land cells that are not part of the glacier, when in reality these cells should not have remaining snow by the end of the melt season. This then results in a positive water balance over those areas. This overproduction of snow can be linked to both a) the overall positive (i.e. too large) precipitation biases, and b) the cold biases we observe in air temperature fields versus those at the nearest NOAA weather stations in Juneau and Skagway (see Section 2.4.2). This finding highlights the challenge of reproducing precipitation in mountain topography, particularly in high latitude ocean-modulated areas where air temperatures are often near the rain-snow threshold, and snow can occur at all months at elevation, conditions that set up great sensitivity within the system due to an ever-changing snowline elevation. Future glacio-hydrological modeling work in coastal areas may benefit from incorporating snowline datasets into their calibration processes.

Model limitations There are several sources of uncertainty within our model results. The SnowModel-HydroFlow routine focuses largely on internal processes within the snowpack, but neglects several elements that may be important to glacier mass balance. In terms of processes that may contribute to additional ice melt, these include geothermal fluxes at the glacier ice/bed interface, as well as dynamical processes such as frictional melting from viscous heating (internal deformation of the ice) or sliding at the glacier bed [*Mernild et al.*, 2014]. Including these processes would require incorporating geothermal flux and ice dynamics components into the model, which is beyond the scope of this study on surface processes.

SnowModel also does not account for changes in glacier geometry resulting from climate forcing, either in terms of reduced area with glacier retreat, or lowered surface elevations with ice thinning. Rather, our simulations use a reference glacier surface representing conditions in the early 2010s, during which the highest-quality imagery was collected and incorporated into the National Elevation Dataset (our DEM), and used to delineate the most accurate glacier outlines to date [*Pfeffer et al.*, 2014]. However, as this time period lies towards the end of our model period, it is likely that our icefield geometry is too low in elevation and too small in extent for the initial years of our simulation. The former would likely cause an overproduction of glacier ice melt and runoff due to higher temperatures at lower elevations, while the latter would cause an underproduction due to insufficient glacial extent. Quantifying each of these would require accurate DEMs for our full model domain from the

1980s, which unfortunately do not exist. The use of a fixed glacier surface may therefore contribute to uncertainties in our cumulative long-term balance for the full model period, particularly during the initial years of our simulation.

From an energy balance standpoint, SnowModel also does not allow for the inclusion of debris cover, i.e. rocks and dust on glacier ice that can impact melt rates. Thin debris layers can enhance melting by lowering the albedo, while thicker debris layers can reduce melting by insulation [*Østrem*, 1959]. However, we do not have any information on debris thickness throughout our coastal domain, and we note that the amount of debris cover accounts for only 4% of the total ice area (and is even smaller at 2.9% for the full Juneau Icefield) [*Kienholz et al.*, 2015], so we consider the effect small. Finally, additional errors may result given that MicroMet does not react to conditions at the surface that may differ from what the MERRA-2 reanalysis initially prescribes. That is, climate conditions are assigned at each grid cell and time step whether or not snow or ice properties have changed [*Mernild et al.*, 2014], although the presence and condition of snow and ice surfaces has the ability to modify local climatic conditions [e.g. *Oerlemans*, 2010].

2.7.2 Glacier mass balance

Glacier change present and future Our model estimates a glacier-wide mass balance rate for 1980 to 2016 of -0.81 [-0.08, +0.11] m w.e. a^{-1} for all ice contained within the domain draining to the coast. To put this estimate in a longer-term context, we compare to future projections from a dynamical (ice flow) study for the Juneau Icefield by *Ziemen et al.* [2016] that modeled possible future mass loss scenarios. In their study, the authors initialized their simulations with a calibrated spin-up for the period 1971 to 2010, followed by projections to 2100. Their model was forced with input climate data downscaled to 20 km from the Coupled Model Intercomparison Project Phase 5 (CMIP5) simulations by the Community Climate System Model 4 [*Gent et al.*, 2011] for 1971 to 2005, and projections to 2100 were forced with the greenhouse gas emissions scenario Representative Concentration Pathway

(RCP) 6.0, representing a middle-of-the-road scenario. For the period 1980 to 2016, we find our mass balance rate estimate of -0.81 [-0.08, +0.11] m w.e. a^{-1} to be more negative than the value from *Ziemen et al.* [2016], at -0.46 m w.e. a^{-1}. While their spin-up estimate was generally tuned to fall between reported values from *Melkonian et al.* [2014] to *Larsen et al.* [2007] rather than being something the model independently discovers, we can nonetheless leverage their results in order to gain understanding of potential future changes beyond our period of study. In their projections, they estimated mass balance rates of -1.59 m w.e. a^{-1} for 2016 to 2050 and -2.53 m w.e. a^{-1} from 2050 to 2099, pointing to a more than five-fold mass loss rate increase over their period of study. The only possibility of stabilization they found was in a constant-climate scenario that maintained the climate at 1971 to 2010 levels, wherein the icefield stabilized at 86% of its 2010 volume.

Literature on current and future climate variables pertaining to glacier mass balance, however, suggests that such a constant-climate scenario is highly unlikely. Several studies on Alaska glaciers have for example linked increasing glacier mass loss rates primarily to increases in summer air temperatures [*Arendt et al.*, 2009; *Criscitiello et al.*, 2010; *O'Neel et al.*, 2014; *Young et al.*, 2018], and indeed summer air temperatures are expected to increase as much as 5°C over northern high latitudes by 2100 [*Koenigk et al.*, 2013]. Maritime glaciers in particular are also highly sensitive to precipitation variations, and especially to decreasing amounts of snow serving to deflect solar radiation (e.g. *De Woul and Hock* [2005]). A recent SnowModel study on snow precipitation trends throughout the Arctic region from 1979 to 2009 found evidence of decreasing trends of annual snow precipitation volumes as well as peak snow water equivalent, with trends along the southeast coast generally among the most negative in Alaska [*Liston and Hiemstra*, 2011]. This trend appears to extend into the future given a climate modeling study for the northern coastal temperate rainforest that projects to 2100 a decrease in snow, despite an increase in total precipitation [*Shanley et al.*, 2015]. Analysis of a downscaled gridded climate product has also found that Alaska is experiencing shifts in the rain-snow fraction towards rain [*McAfee et al.*, 2014], a phenomenon to which coastal glaciers have been found to be especially sensitive [*Moore et al.*, 2009], and which can exert a strong influence in our domain given the steep topography and resulting sensitivity to changing snowline elevation. Furthermore, a modeling investigation on maritime Arctic glaciers shows that a 1°C increase in air temperature can only be offset by a 50% increase in snow [*De Woul and Hock*, 2005], an unlikely occurrence given all the mounting evidence for decreased snow and increased rain.

Taken together, we see little evidence that a constant-climate scenario will occur in this region, given current and future trends in increasing air temperature and decreasing snow. As such, there is little indication that glacier mass loss acceleration in the western Juneau Icefield area will decrease or reverse. In fact, our 1980 to 2016 mass loss rate, being more negative than *Ziemen et al.* [2016] to begin with, may point to even stronger accelerations to 2100 than their anticipated five-fold mass loss rate increase. This could result in an even greater reduction in size than their estimated 63% volume loss and 62% area loss by 2100, an outcome that would substantially alter downstream hydrology.

Glaciological linkage to total runoff We find that mean annual total runoff from our coastal watershed domain is 20.0 $km^3\ a^{-1}$ for 1980 to 2016. On a seasonal basis, total runoff ranges from a minimum of 0.004 km^3 in February to a maximum of 5.0 km^3 in July (Figure 2.6). We observe a single peak in runoff in summer associated with glacier contributions and no secondary peak associated with spring snowmelt. This is consistent with *Hill et al.* [2015] who observed in a modeling study of 1960 to 2010 freshwater discharge a single peak in the hydrograph of the southern Gulf of Alaska region versus a dual peak in the north. Of the total runoff, 55% is sourced from glacier surfaces, a higher value than previous regional estimates for the Gulf of Alaska at 38 to 47% [*Neal et al.*, 2010; *Beamer et al.*, 2016]. The contribution of glacier volume loss to total runoff in our coastal domain is 12% for 1980 to 2016, as compared to regional Gulf of Alaska estimates of 7 to 10% [*Neal et al.*, 2010; *Hill et al.*, 2015; *Beamer et al.*, 2016]. The larger glacier contributions here are likely due to the greater extent of ice cover in our domain (44%) relative to the larger Gulf of Alaska domain (∼17%).

Our results indicate that total annual runoff over the 36 year period of study is not correlated with annual glacier mass balance values. This shows that, in coastal environments, even large glaciers or icefields experiencing mass loss may not exert a strong control on total runoff given an overwhelming precipitation signal. This emphasizes the importance of not using annual mass balance values as a proxy for streamflow, and is supported by similar findings for another maritime Alaska glacier basin in *O'Neel et al.* [2014].

We also find that glacier runoff volumes are more strongly correlated with total runoff ($r^2 = 0.90$) than with glacier ice melt ($r^2 = 0.68$), suggesting that glacier runoff is more strongly controlled by overall precipitation events than glacier ice melt. This decoupling between glacier ice melt and runoff is likely to be further enhanced in the future, given the projected change in rain/snow fraction towards rain [*McAfee et al.*, 2014; *Shanley et al.*, 2015], which is likely to contribute proportionally more to glacier runoff than to glacier ice melt.

2.7.3 Freshwater runoff

Glacier ice melt and glacier runoff trends present and future Examining the annual volume of glacier ice melt over our study period, our results suggest a strongly increasing trend of nearly 10% per decade. Further evidence of increasing glacier ice melt rates is seen in the increasing amplitudes in Figure 2.10f in recent decades, as well as in the increasing anomalies towards the end of the study period in Figure 2.11. This finding indicates that in this high latitude maritime glacierized domain, the annual volume of glacier ice melt has not yet reached its maximum and will continue to increase to a yet unknown peak before it begins to decrease. This increasing signal is more difficult to detect (both in terms of magnitude as well as statistical metrics) in annual volumes of glacier runoff (+3% increase) and in total runoff (+1.4% increase). We expect this given increasing contributions from precipitation, which is prone to high variability in this area, as seen in Figure 2.10 and found in *Bieniek* *et al.* [2014]. Nonetheless our findings of an increase in total runoff are consistent with an analysis of stream gauge records from the Wolverine Glacier, another maritime glacier watershed in Alaska that experienced a 23% increase in summer streamflow (i.e. a measure of total runoff) between 1966 to 2011 [*O'Neel et al.*, 2014]. While that study was based on gauge measurements and therefore lacked the ability to partition hydrological components, our modeling approach allows us to identify that glacier ice melt is most responsible for the increase in total runoff in our coastal glacierized domain.

As well as contributing new information on current freshwater discharge changes at the local scale in Alaska, our results can be placed in context with other local and regional studies that project future changes as well. First, our finding that glacier ice melt is the principal driver of the total runoff increase is supported by modeling results to 2100 from *Valentin et al.* [2018] for the nearby Copper River watershed in Southcentral Alaska. Those authors projected under the moderate and high emissions scenarios RCP4.5 and RCP8.5 an increase in total runoff of 17 to 48%, respectively, driven primarily by a glacier ice melt increase of 13 to 53%. While that study did not examine the timing of peak water in the watershed, a different study that modeled global glacier runoff changes to 2100 under RCP4.5 found that the Gulf of Alaska is the region projected to reach peak water the latest (between 2060 to 2070) of all regions globally [*Huss and Hock*, 2018]. Although the authors used a calibration approach that leveraged regional rather than local observations of mass balance and did not include comparison to local stream gauge data, their results nonetheless represent a moderate scenario for the region as a whole.

Altogether, our findings and these studies, along with projections for strong and continued warming at high latitudes [*Koenigk et al.*, 2013], lead us to expect that glacier runoff in the western Juneau Icefield will continue to increase before such time as the glaciers lose enough volume to reverse this trend. Although accurately predicting when this will occur would require coupling a hydrological routing model to glacier mass balance modeling projections such as those in *Ziemen et al.* [2016], which is beyond the scope of this hindcasting study, we speculate that given regional projections for the Gulf of Alaska of a peak water period near 2060 to 2070 [*Huss and Hock*, 2018], it will be several decades before the phenomenon occurs in our domain.

A changing hydrological regime Even with a strong increasing trend in annual glacier ice melt volumes, total runoff in this coastal glacierized area shows evidence of only a slightly increasing trend. Our findings instead reveal that the most prominent signs of hydrological regime change in this region are with respect to the timing and biogeochemical characteristics of the water being delivered downstream.

One indicator of these water quality changes is an increase in the magnitude of the maximum daily volume of glacier ice melt at a rate of 10% per decade. This increase has the potential, on those maximum flow days, to substantially modify freshwater conditions downstream as the proportion of glacier ice melt input grows relative to other freshwater sources. Additionally, although we do not detect robust trends in the onset, end, or subsequent length of the glacier ice melt season, our results suggest a marked increase in glacier ice melt delivery during the spring months, which in essence serves to shift periods of high glacier ice melt earlier into the year (Table 2.3, Figure 2.10). This earlier arrival signals a shift towards a hydrograph more closely resembling that of snowmelt-dominated basins. This finding is supported by regional analyses of temperature records in western North America over the past 50 years that show an asymmetry in warming of spring versus fall, which can be explained by seasonal differences in atmospheric circulation regimes [*Abatzoglou and Redmond*, 2007]. However, in projections to 2100, *Koenigk et al.* [2013] found the most pronounced increases in air temperature in Alaska are likely to occur in winter and fall. We suggest, therefore, that there is potential for future increases in glacier ice melt and glacier runoff volumes in the fall season as well.

Several downstream impacts have occurred since the 1980s with a 16% increase per decade in springtime glacier ice melt and a corresponding 7% increase in glacier runoff. Given the tight relationship between stream temperature and glacier cover in this area [*Fellman et al.*, 2014], our results suggest that stream temperatures during the spring months have likely become lower on account of the higher proportion of glacier ice melt input. In addition, we speculate there has been an increase in turbidity stemming from the influx of glacially-eroded sediment along with increased glacier melt [*Milner et al.*, 2017]. Minerals and limiting nutrients contained therein are in turn likely delivered earlier and at larger magnitudes, including phosphorous, nitrogen, iron, and bioavailable organic carbon to riverine and estuarine food webs [*O'Neel et al.*, 2015].

In addition to altering stream conditions, the biogeophysical signature of glacier runoff also extends kilometers into Gulf of Alaska fjords, by setting up a stratified water column with fresh, cold, turbid, and generally nutrient-rich water at the ocean surface [*Arimitsu et al.*, 2016]. Therefore, changes in the timing of arrival of large volumes of glacier runoff will influence both estuary and stream conditions. In the estuary, glacially-influenced environmental gradients explain much of the distribution and abundance of phytoplankton, which in turn drives higher trophic level food web structure for copepods, fish, and sea birds [*Arimitsu et al.*, 2016]. In rivers and streams, both temperature and water clarity are key variables for Pacific salmon spawning ground habitat selection [*Lorenz and Filer*, 1989], particularly given the sharp thermal limits of these species [*Welch et al.*, 1998; *Richter and Kolmes*, 2005]. Indeed, evidence is already mounting that populations among several Pacific salmon species are migrating to freshwater up to 0.5 days earlier per year than they did historically [*Kovach et al.*, 2015]. Although the mechanisms for the earlier timing remain complex, freshwater conditions in the riverine environment may contribute, given freshwater conditions that may support migration earlier in the year. For other populations, however, there is some concern that eventual decreased summer flows may lead to higher water temperatures and in turn lead to reduced salmonid function [*Richter and Kolmes*, 2005] as well as a reduction in spawning habitat [*Wobus et al.*, 2015]. These latter concerns may come to pass after the period of peak water has passed in this domain.

Given our findings that peak glacier ice melt volumes are arriving earlier and that annual and spring volumes of freshwater (glacier ice melt, glacier runoff, and total runoff) are increasing, changes to freshwater thermal regimes and riverine nutrient export have likely already taken place in this high latitude coastal ecosystem. Moreover, under continued warming and a decrease in precipitation as snow, projections continue to call for substantial and varied change to these and other hydroecological variables into the future [*Shanley et al.*, 2015].

2.8 Conclusions

This study applied the coupled glacio-hydrological model SnowModel-HydroFlow to estimate daily freshwater runoff from 1980 to 2016 for the coastal watershed draining the western Juneau Icefield in Southeast Alaska, an area of 6405 km^2 with 44% glacier cover. We find a strongly increasing trend in annual glacier ice melt production (9.6% $decade^{-1}$), with especially pronounced increases during spring months (16.5% $decade^{-1}$). This increase can also be detected in both glacier runoff (3.0% for annual volumes, 6.8% for spring volumes) and total runoff (1.4%, 2.7%). Together, these results suggest that this particular region has not yet passed the period of peak water associated with a persistent negative mass balance, likely on account of the extensive glacier coverage.

Unlike studies based on stream gauge data, our model results afford the opportunity to identify that glacier ice melt is the likely hydrological driver behind increases in total runoff seen over the past several decades. Moreover, our study contributes new and affirmative knowledge towards the question of whether glacier runoff trends can be detected in maritime climates with high precipitation variability.

Overall in this domain, glacier runoff contributes 55% of total runoff, including 12% from non-renewable glacier volume loss. Total runoff in the domain is found not to be correlated to annual glacier mass balance, supporting the paradigm that advises against using annual balances as a proxy for glacier runoff volumes. Given projection studies that predict increasing glacier volume loss for the Juneau Icefield through 2100, we anticipate ongoing glacier ice melt increases decades into the future, until such point as peak water is passed and the contribution of glacier ice melt and glacier runoff to the domain begins to change once more.

We find that changes in runoff timing and biogeochemical properties are the aspects of the hydrological regime undergoing the greatest changes in this coastal glacierized environment, with substantial impacts for downstream ecosystems. In particular, the earlier arrival of large volumes of glacier ice melt in spring is likely exerting an influence on stream temperature and clarity, a point of concern for downstream species such as salmon that have evolved to survive in particular freshwater conditions.

Ultimately, our results emphasize that even in maritime climates with high precipitation variability, high latitude glacierized watersheds are experiencing perceptible and ongoing hydrological regime change given persistent glacier volume loss.

2.9 References

Abatzoglou, J., and K. Redmond (2007), Asymmetry between trends in spring and autumn temperature and circulation regimes over western North America, *Geophysical Research Letters*, *34*(18).

Amrhein, V., S. Greenland, and B. McShane (2019), Retire statistical significance, *Nature*, *567*.

Arendt, A., J. Walsh, and W. Harrison (2009), Changes of glaciers and climate in northwestern North America during the late 20th century, *Journal of Climate*, *22*(15), 4117–4134.

Arendt, A., S. Luthcke, A. Gardner, S. O'Neel, D. Hill, G. Moholdt, and W. Abdalati (2013), Analysis of a GRACE global mascon solution for Gulf of Alaska glaciers, *Journal of Glaciology*, *59*(217), 913.

Arimitsu, M. L., J. F. Piatt, and F. Mueter (2016), Influence of glacier runoff on ecosystem structure in Gulf of Alaska fjords, *Marine Ecology Progress Series*, *560*, 19–40.

Beamer, J., D. Hill, A. Arendt, and G. Liston (2016), High-resolution modeling of coastal freshwater discharge and glacier mass balance in the Gulf of Alaska watershed, *Water Resources Research*.

Berthier, E., E. Schiefer, G. Clarke, B. Menounos, and F. Rémy (2010), Contribution of Alaskan glaciers to sea level rise derived from satellite imagery, *Nature Geoscience*, *3*, 92–95, doi:10.1038/NGEO737.

Berthier, E., C. Larsen, W. J. Durkin, M. J. Willis, and M. E. Pritchard (2018), Brief communication: Unabated wastage of the Juneau and Stikine icefields (southeast Alaska) in the early 21st century, *The Cryosphere*, *12*(4), 1523–1530.

Bieniek, P. A., J. E. Walsh, R. L. Thoman, and U. S. Bhatt (2014), Using climate divisions to analyze variations and trends in Alaska temperature and precipitation, *Journal of Climate*, *27*(8), 2800–2818.

Bosilovich, M., R. Lucchesi, and M. Suarez (2015), MERRA-2: File specification.

Boyce, E. S., R. J. Motyka, and M. Truffer (2007), Flotation and retreat of a lake-calving terminus, Mendenhall Glacier, Southeast Alaska, USA, *Journal of Glaciology*, *53*(181), 211–224.

Carnahan, E., J. Amundson, and E. Hood (2018), Impact of glacier loss on annual basin water yields, *Hydrology and Earth System Sciences Discussions*, pp. 1–20, doi:10.5194/hess-2018-509.

Cohen, J. (2016), The earth is round (p $\leq$ .05), in *What if there were no significance tests?*, pp. 69–82, Routledge.

Criscitiello, A. S., M. A. Kelly, and B. Tremblay (2010), The response of Taku and Lemon Creek glaciers to climate, *Arctic, Antarctic, and Alpine Research*, *42*(1), 34–44.

Crusius, J., A. W. Schroth, S. Gasso, C. M. Moy, R. C. Levy, and M. Gatica (2011), Glacial flour dust storms in the Gulf of Alaska: Hydrologic and meteorological controls and their importance as a source of bioavailable iron, *Geophysical Research Letters*, *38*(6).

Cuffey, K. M., and W. S. B. Paterson (2010), *The Physics of Glaciers*, Academic Press.

Daly, C., M. Halbleib, J. I. Smith, W. P. Gibson, M. K. Doggett, G. H. Taylor, J. Curtis, and P. P. Pasteris (2008), Physiographically sensitive mapping of climatological temperature and precipitation across the conterminous United States, *International Journal of Climatology: A Journal of the Royal Meteorological Society*, *28*(15), 2031–2064.

De Woul, M., and R. Hock (2005), Static mass-balance sensitivity of Arctic glaciers and ice caps using a degree-day approach, *Annals of Glaciology*, *42*(1), 217–224.

Fellman, J. B., S. Nagorski, S. Pyare, A. W. Vermilyea, D. Scott, and E. Hood (2014), Stream temperature response to variable glacier coverage in coastal watersheds of Southeast Alaska, *Hydrological Processes*, *28*(4), 2062–2073.

Fellman, J. B., E. Hood, P. A. Raymond, J. Hudson, M. Bozeman, and M. Arimitsu (2015), Evidence for the assimilation of ancient glacier organic carbon in a proglacial stream food web, *Limnology and Oceanography*, *60*(4), 1118–1128.

Fischer, G., S. Nachtergaele, H. Prieler, L. van Velthuizen, and D. Verelst (2008), Global Agro-Ecological Zones assessment for agriculture (GAEZ 2008), *IIASA, Laxenburg, Austria and FAO, Rome, Italy.*

Fountain, A. G., and W. V. Tangborn (1985), The effect of glaciers on streamflow variations, *Water Resources Research*, *21*(4), 579–586.

Ganey, G. Q., M. G. Loso, A. B. Burgess, and R. J. Dial (2017), The role of microbes in snowmelt and radiative forcing on an Alaskan icefield, *Nature Geoscience*, *10*(10), 754.

Gardner, A. S., M. J. Sharp, R. M. Koerner, C. Labine, S. Boon, S. J. Marshall, D. O. Burgess, and D. Lewis (2009), Near-surface temperature lapse rates over Arctic glaciers and their implications for temperature downscaling, *Journal of Climate*, *22*(16), 4281–4298.

Gelaro, R., W. McCarty, M. J. Suárez, R. Todling, A. Molod, L. Takacs, C. A. Randles, A. Darmenov, M. G. Bosilovich, R. Reichle, et al. (2017), The Modern-Era Retrospective analysis for Research and Applications, version 2 (MERRA-2), *Journal of Climate*, *30*(14), 5419–5454.

Gent, P. R., G. Danabasoglu, L. J. Donner, M. M. Holland, E. C. Hunke, S. R. Jayne, D. M. Lawrence, R. B. Neale, P. J. Rasch, M. Vertenstein, et al. (2011), The Community Climate System Model version 4, *Journal of Climate*, *24*(19), 4973–4991.

Gleick, P. H., and M. Palaniappan (2010), Peak water limits to freshwater withdrawal and use, *Proceedings of the National Academy of Sciences*, *107*(25), 11,155–11,162.

Halsey, L. G. (2019), The reign of the p-value is over: What alternative analyses could we employ to fill the power vacuum?, *Biology Letters*, *15*(5), 20190,174.

Halsey, L. G., D. Curran-Everett, S. L. Vowler, and G. B. Drummond (2015), The fickle p value generates irreproducible results, *Nature Methods*, *12*(3), 179.

Helsel, D. R., and R. M. Hirsch (2002), *Statistical methods in water resources*, vol. 323, US Geological Survey Reston, VA.

Hill, D., N. Bruhis, S. Calos, A. Arendt, and J. Beamer (2015), Spatial and temporal variability of freshwater discharge into the Gulf of Alaska, *Journal of Geophysical Research: Oceans*, *120*(2), 634–646.

Hock, R., and M. Huss (2015), A new model for global glacier change and sea-level rise, *Frontiers in Earth Science*, *3*, 1–22.

Homer, C., J. Dewitz, L. Yang, S. Jin, P. Danielson, G. Xian, J. Coulston, N. Herold, J. Wickham, and K. Megown (2015), Completion of the 2011 National Land Cover Database for the conterminous United States – representing a decade of land cover change information, *Photogrammetric Engineering & Remote Sensing*, *81*(5), 345–354.

Hood, E., and L. Berner (2009), The effect of changing glacial coverage on the physical and biogeochemical properties of coastal streams in southeastern Alaska, *Journal of Geophysical Research*, *114*(13), G03,001, doi:10.1029/2009JG000971.

Hood, E., and D. Scott (2008), Riverine organic matter and nutrients in Southeast Alaska affected by glacial coverage, *Nature Geoscience*, *1*(9), 583–587.

Hood, E., J. Fellman, R. Spencer, P. Hernes, R. Edwards, D. D'Amore, and D. Scott (2009), Glaciers as a source of ancient and labile organic matter to the marine environment, *Nature*, *462*(7276), 1044–1048, doi:10.1038/nature08580.

Hoogeveen, J., J.-M. Faurès, L. Peiser, J. Burke, and N. Giesen (2015), GlobWat–a global water balance model to assess water use in irrigated agriculture, *Hydrology and Earth System Sciences*, *19*(9), 3829–3844.

Huss, M., and R. Hock (2018), Global-scale hydrological response to future glacier mass loss, *Nature Climate Change*, *8*(2), 135.

Jansson, P., R. Hock, and T. Schneider (2003), The concept of glacier storage: A review, *Journal of Hydrology*, *282*(1-4), 116–129.

Kienholz, C., S. Herreid, J. Rich, A. Arendt, R. Hock, and E. Burgess (2015), Derivation and analysis of a complete modern-date glacier inventory for Alaska and northwest Canada, *Journal of Glaciology*, *61*(227), 403.

Koenigk, T., L. Brodeau, R. G. Graversen, J. Karlsson, G. Svensson, M. Tjernström, U. Willén, and K. Wyser (2013), Arctic climate change in 21st century CMIP5 simulations with EC-Earth, *Climate Dynamics*, *40*(11-12), 2719–2743.

Komatsu, H. (2005), Forest categorization according to dry-canopy evaporation rates in the growing season: Comparison of the Priestley–Taylor coefficient values from various observation sites, *Hydrological Processes: An International Journal*, *19*(19), 3873–3896.

Kovach, R. P., S. C. Ellison, S. Pyare, and D. A. Tallmon (2015), Temporal patterns in adult salmon migration timing across southeast Alaska, *Global Change Biology*, *21*(5), 1821–1833.

Lader, R., U. S. Bhatt, J. E. Walsh, T. S. Rupp, and P. A. Bieniek (2016), Two-meter temperature and precipitation from atmospheric reanalysis evaluated for Alaska, *Journal of Applied Meteorology and Climatology*, *55*(4), 901–922.

Lang, H. (1986), Forecasting meltwater runoff from snow-covered areas and from glacier basins, in *River flow modelling and forecasting*, pp. 99–127, Springer.

Larsen, C., R. Motyka, J. Freymuller, K. Echelmeyer, and E. Ivins (2005), Rapid viscoelastic uplift in Southeast Alaska caused by post-Little Ice Age glacial retreat, *Earth and Planetary Science Letters*, *237*, 548–560.

Larsen, C., R. Motyka, A. Arendt, K. Echelmeyer, and P. Geissler (2007), Glacier changes in southeast Alaska and northwest British Columbia and contribution to sea level rise, *Journal of Geophysical Research*, *112*(1), F01,007, doi:10.1029/2006JF000586.

Lawson, E. C., J. L. Wadham, M. Tranter, M. Stibal, G. P. Lis, C. E. Butler, J. Laybourn-Parry, P. Nienow, D. Chandler, and P. Dewsbury (2014), Greenland Ice Sheet exports labile organic carbon to the Arctic oceans, *Biogeosciences*, *11*(14), 4015–4028.

Lenaerts, J., J. H. Angelen, M. R. Broeke, A. S. Gardner, B. Wouters, and E. Meijgaard (2013), Irreversible mass loss of Canadian Arctic Archipelago glaciers, *Geophysical Research Letters*, *40*(5), 870–874.

Lindsay, R., M. Wensnahan, A. Schweiger, and J. Zhang (2014), Evaluation of seven different atmospheric reanalysis products in the Arctic, *Journal of Climate*, *27*(7), 2588–2606.

Liston, G. E., and K. Elder (2006a), A distributed snow-evolution modeling system (SnowModel), *Journal of Hydrometeorology*, *7*(6), 1259–1276.

Liston, G. E., and K. Elder (2006b), A meteorological distribution system for high-resolution terrestrial modeling (MicroMet), *Journal of Hydrometeorology*, *7*(2), 217–234.

Liston, G. E., and C. A. Hiemstra (2008), A simple data assimilation system for complex snow distributions (SnowAssim), *Journal of Hydrometeorology*, *9*(5), 989–1004.

Liston, G. E., and C. A. Hiemstra (2011), The changing cryosphere: Pan-Arctic snow trends (1979-2009), *Journal of Climate*, *24*(21), 5691–5712.

Liston, G. E., and S. H. Mernild (2012), Greenland freshwater runoff. Part I: A runoff routing model for glaciated and nonglaciated landscapes (HydroFlow), *Journal of Climate*, *25*(17), 5997–6014.

Liston, G. E., and M. Sturm (2002), Winter precipitation patterns in Arctic Alaska determined from a blowing-snow model and snow-depth observations, *Journal of Hydrometeorology*, *3*(6), 646–659.

Loomis, B., S. Luthcke, and T. Sabaka (2019), Regularization and error characterization of GRACE mascons, *Journal of Geodesy*, pp. 1–18.

Lorenz, J. M., and J. H. Filer (1989), Spawning habitat and redd characteristics of sockeye salmon in the glacial Taku River, British Columbia and Alaska, *Transactions of the American Fisheries Society*, *118*(5), 495–502.

Luthcke, S., T. Sabaka, B. Loomis, A. Arendt, J. McCarthy, and J. Camp (2013), Antarctica, Greenland and Gulf of Alaska land-ice evolution from an iterated GRACE global mascon solution, *Journal of Glaciology*, *59*(216), 613–631, doi:10.3189/2013JoG12J147.

Masson-Delmotte, V., P. Zhai, H.-O. Prtner, D. Roberts, J. Skea, P. Shukla, A. Pirani, W. Moufouma-Okia, C. Pan, R. Pidcock, S. Connors, J. Matthews, Y. Chen, X. Zhou, M. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (2018), IPCC, 2018: Summary for Policymakers. In: Global Warming of 1.5C. An IPCC Special Report on the impacts of global warming of 1.5C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty, *Technical report*, World Meteorological Organization.

McAfee, S. A., J. Walsh, and T. S. Rupp (2014), Statistically downscaled projections of snow/rain partitioning for Alaska, *Hydrological Processes*, *28*(12), 3930–3946.

McGrath, D., L. Sass, S. O'Neel, A. Arendt, G. Wolken, A. Gusmeroli, C. Kienholz, and C. McNeil (2015), End-of-winter snow depth variability on glaciers in Alaska, *Journal of Geophysical Research: Earth Surface*, *120*(8), 1530–1550.

McNeil, C. J., S. W. Campbell, S. O'Neel, and E. H. Baker (2019a), Glacier-wide mass balance and compiled data inputs: Juneau Icefield glaciers, doi:10.5066/P9YBZ36F.

McNeil, C. J., L. C. Sass, C. E. Florentine, E. H. Baker, E. H. Peitzsch, E. N. Whorton, Z. S. Miller, D. B. Fagre, A. M. Clark, and S. R. O'Neel (2019b), Glacier-wide mass balance and compiled data inputs: Juneau Icefield glaciers (ver. 4.0, November 2019), doi:10.5066/F7HD7SRF.

Melkonian, A. K., M. J. Willis, and M. E. Pritchard (2014), Satellite-derived volume loss rates and glacier speeds for the Juneau Icefield, Alaska, *Journal of Glaciology*, *60*(222), 743–760.

Mernild, S. H., and G. E. Liston (2012), Greenland freshwater runoff. Part II: Distribution and trends, 1960–2010, *Journal of Climate*, *25*(17), 6015–6035.

Mernild, S. H., G. E. Liston, B. Hasholt, and N. T. Knudsen (2006), Snow distribution and melt modeling for Mittivakkat Glacier, Ammassalik Island, southeast Greenland, *Journal of Hydrometeorology*, *7*(4), 808–824.

Mernild, S. H., G. E. Liston, and B. Hasholt (2007), Snow-distribution and melt modelling for glaciers in Zackenberg river drainage basin, north-eastern Greenland, *Hydrological Processes*, *21*(24), 3249–3263, doi:10.1002/hyp.6500.

Mernild, S. H., G. E. Liston, C. A. Hiemstra, and J. H. Christensen (2010), Greenland ice sheet surface mass-balance modeling in a 131-yr perspective, 1950-2080, *Journal of Hydrometeorology*, *11*(1), 3–25.

Mernild, S. H., G. E. Liston, and C. A. Hiemstra (2014), Northern hemisphere glacier and ice cap surface mass balance and contribution to sea level rise, *Journal of Climate*, *27*(15), 6051–6073.

Mernild, S. H., D. M. Holland, D. Holland, A. Rosing-Asvid, J. C. Yde, G. E. Liston, and K. Steffen (2015), Freshwater flux and spatiotemporal simulated runoff variability into Ilulissat Icefjord, West Greenland, linked to salinity and temperature Observations near tidewater glacier margins obtained using instrumented ringed seals, *Journal of Physical Oceanography*, *45*(5), 1426–1445.

Mernild, S. H., G. E. Liston, C. Hiemstra, and R. Wilson (2017), The Andes Cordillera. Part III: Glacier surface mass balance and contribution to sea level rise (1979–2014), *International Journal of Climatology*, *37*(7), 3154–3174.

Mesinger, F., G. DiMego, E. Kalnay, K. Mitchell, P. C. Shafran, W. Ebisuzaki, D. Jović, J. Woollen, E. Rogers, E. H. Berbery, et al. (2006), North American Regional Reanalysis, *Bulletin of the American Meteorological Society*, *87*(3), 343–360.

Milner, A. M., K. Khamis, T. J. Battin, J. E. Brittain, N. E. Barrand, L. Füreder, S. Cauvy-Fraunié, G. M. Gíslason, D. Jacobsen, D. M. Hannah, et al. (2017), Glacier shrinkage driving global changes in downstream systems, *Proceedings of the National Academy of Sciences*, *114*(37), 9770–9778.

Moore, R. D., S. W. Fleming, B. Menounos, R. Wheate, A. Fountain, K. Stahl, K. Holm, and M. Jakob (2009), Glacier change in western North America: Implications for hydrology, geomorphic hazards and water quality, *Hydrological Processes*, *23*, 42–61.

Motyka, R. J., S. O'Neel, C. L. Connor, and K. A. Echelmeyer (2002), Twentieth century thinning of Mendenhall Glacier, Alaska, and its relationship to climate, lake calving, and glacier run-off, *Global and Planetary Change*, *35*(1-2), 93–112.

Nagorski, S. A., S. D. Kaspari, E. Hood, J. B. Fellman, and S. M. Skiles (2019), Radiative forcing by dust and black carbon on the Juneau Icefield, Alaska, *Journal of Geophysical Research: Atmospheres*, *124*(7), 3943–3959.

Nash, J. E., and J. V. Sutcliffe (1970), River flow forecasting through conceptual models part I: A discussion of principles, *Journal of Hydrology*, *10*(3), 282–290.

Neal, E., E. Hood, and K. Smikrud (2010), Contribution of glacier runoff to freshwater discharge into Gulf of Alaska, *Geophysical Research Letters*, *37*(6), L06,404, doi:10.1029/2010GL042385.

Oerlemans, J. (2010), *The Microclimate of Valley Glaciers*, Igitur, Utrecht Publishing & Archiving Services.

O'Neel, S., E. Hood, A. Arendt, and L. Sass (2014), Assessing streamflow sensitivity to variations in glacier mass balance, *Climatic Change*, *123*(2), 329–341.

O'Neel, S., E. Hood, A. L. Bidlack, S. W. Fleming, M. L. Arimitsu, A. Arendt, E. Burgess, C. J. Sergeant, A. H. Beaudreau, K. Timm, et al. (2015), Icefield-to-ocean linkages across the northern Pacific coastal temperate rainforest ecosystem, *BioScience*, *65*(5), 499–512.

O'Neel, S., D. McGrath, G. Wolken, E. Whorton, S. Candela, L. Sass, C. McNeil, E. Baker, E. Peitzsch, D. Fagre, A. Clark, C. Florentine, Z. Miller, J. Christian, K. Christianson, E. Babcock, M. Loso, A. Arendt, E. Burgess, and A. Gusmeroli (2018), Ground penetrating radar data on North American glaciers, version 2.1, U.S. Geological Survey data release, doi:10.5066/F7M043G7.

Østrem, G. (1959), Ice melting under a thin layer of moraine, and the existence of ice cores in moraine ridges, *Geografiska Annaler*, *41*(4), 228–230.

Østrem, G., and M. Brugman (1991), Glacier mass-balance measurements, *Technical report*, National Hydrology Research Institute.

Peltier, W. (2004), Global glacial isostasy and the surface of the Ice-Age Earth: the ICE-5G (VM2) model and GRACE, *Annual Review of Earth and Planetary Sciences*, *32*, 111–149.

Pelto, M., J. Kavanaugh, and C. McNeil (2013), Juneau Icefield mass balance program 1946–2011, *Earth System Science Data*, *5*(2), 319–330.

Pfeffer, W. T., A. A. Arendt, A. Bliss, T. Bolch, J. G. Cogley, A. S. Gardner, J.-O. Hagen, R. Hock, G. Kaser, C. Kienholz, et al. (2014), The Randolph Glacier Inventory: A globally complete inventory of glaciers, *Journal of Glaciology*, *60*(221), 537–552.

Priestley, C., R. Taylor, et al. (1972), On the assessment of surface heat flux and evaporation using large-scale parameters, *Monthly Weather Review*, *100*(2), 81–92.

Radić, V., and R. Hock (2014), Glaciers in the Earth's hydrological cycle: Assessments of glacier mass and runoff changes on global and regional scales, *Surveys in Geophysics*, *35*(3), 813–837.

Ramage, J. M., B. L. Isacks, and M. M. Miller (2000), Radar glacier zones in Southeast Alaska, USA: Field and satellite observations, *Journal of Glaciology*, *46*(153), 287–296.

Reager, J., A. Gardner, J. Famiglietti, D. Wiese, A. Eicker, and M.-H. Lo (2016), A decade of sea level rise slowed by climate-driven hydrology, *Science*, *351*(6274), 699–703.

Reichle, R. H., C. S. Draper, Q. Liu, M. Girotto, S. P. Mahanama, R. D. Koster, and G. J. De Lannoy (2017), Assessment of MERRA-2 land surface hydrology estimates, *Journal of Climate*, *30*(8), 2937–2960.

Richter, A., and S. A. Kolmes (2005), Maximum temperature limits for Chinook, coho, and chum salmon, and steelhead trout in the Pacific Northwest, *Reviews in Fisheries science*, *13*(1), 23–49.

Rienecker, M. M., M. J. Suarez, R. Gelaro, R. Todling, J. Bacmeister, E. Liu, M. G. Bosilovich, S. D. Schubert, L. Takacs, G.-K. Kim, et al. (2011), MERRA: NASA's Modern-Era Retrospective analysis for Research and Applications, *Journal of Climate*, *24*(14), 3624–3648.

Rodell, M., P. Houser, U. Jambor, J. Gottschalck, K. Mitchell, C.-J. Meng, K. Arsenault, B. Cosgrove, J. Radakovich, M. Bosilovich, J. K. Entin, J. P. Walker, D. Lohmann, and D. Toll (2004), The Global Land Data Assimilation System, *Bulletin of the American Meteorological Society*, *85*(3), 381–394.

Rohrer, M. (1989), Determination of the transition air temperature from snow to rain and intensity of precipitation, in *WMO IASH ETH International Workshop on Precipitation Measurement*, pp. 475–582.

Roth, A., R. Hock, T. V. Schuler, P. A. Bieniek, M. Pelto, and A. Aschwanden (2018), Modeling winter precipitation over the Juneau Icefield, Alaska, using a linear model of orographic precipitation, *Frontiers in Earth Science*, *6*, 20.

Royer, T. C. (1998), Coastal processes in the northern North Pacific, *The Global Coastal Ocean: Regional Studies and Synthesis*.

Saha, S., S. Moorthi, H.-L. Pan, X. Wu, J. Wang, S. Nadiga, P. Tripp, R. Kistler, J. Woollen, D. Behringer, et al. (2010), The NCEP climate forecast system reanalysis, *Bulletin of the American Meteorological Society*, *91*(8), 1015–1058.

Shanley, C. S., S. Pyare, M. I. Goldstein, P. B. Alaback, D. M. Albert, C. M. Beier, T. J. Brinkman, R. T. Edwards, E. Hood, et al. (2015), Climate change implications in the northern coastal temperate rainforest of North America, *Climatic Change*, *130*(2).

Shi, T., D. Guan, A. Wang, J. Wu, C. Jin, and S. Han (2008), Comparison of three models to estimate evapotranspiration for a temperate mixed forest, *Hydrological Processes: An International Journal*, *22*(17), 3431–3443.

Stabeno, P., N. Bond, A. Hermann, N. Kachel, C. Mordy, and J. Overland (2004), Meteorology and oceanography of the northern Gulf of Alaska, *Continental Shelf Research*, *24*(7-8), 859–897.

Tomczak, M., and E. Tomczak (2014), The need to report effect size estimates revisited. An overview of some recommended measures of effect size, *Trends in Sport Sciences*, *21*(1).

Truffer, M., R. J. Motyka, M. Hekkers, I. M. Howat, and M. A. King (2009), Terminus dynamics at an advancing glacier: Taku Glacier, Alaska, *Journal of Glaciology*, *55*(194), 1052–1060.

Valentin, M., T. Hogue, and L. Hay (2018), Hydrologic regime changes in a high-latitude glacierized watershed under future climate conditions, *Water*, *10*(2), 128.

Welch, D., Y. Ishida, and K. Nagasawa (1998), Thermal limits and ocean migrations of sockeye salmon (Oncorhynchus nerka): Long-term consequences of global warming, *Canadian Journal of Fisheries and Aquatic Sciences*, *55*(4), 937–948.

Wilson, D. J. (2019), The harmonic mean p-value for combining dependent tests, *Proceedings of the National Academy of Sciences*, *116*(4), 1195–1200.

Wobus, C., R. Prucha, D. Albert, C. Woll, M. Loinaz, and R. Jones (2015), Hydrologic alterations from climate change inform assessment of ecological risk to Pacific salmon in Bristol Bay, Alaska, *PloS one*, *10*(12), e0143,905.

Wouters, B., J. Bonin, D. Chambers, R. Riva, I. Sasgen, and J. Wahr (2014), GRACE, time-varying gravity, Earth system dynamics and climate change, *Reports on Progress in Physics*, *77*(11), 116,801.

Wrzesien, M. L., M. T. Durand, and T. M. Pavelsky (2019), A reassessment of North American river basin cool-season precipitation: Developments from a new mountain climatology dataset, *Water Resources Research*, doi:10.1029/2018WR024106.

Young, J. C. (2019), Gilkey Glacier mass balance point observations 2013-2015, Southeast Alaska, HydroShare, doi:10.4211/hs.275f3521cc834467a34c051a716a3b30.

Young, J. C., A. Arendt, R. Hock, and E. Pettit (2018), The challenge of monitoring glaciers with extreme altitudinal range: Mass-balance reconstruction for Kahiltna Glacier, Alaska, *Journal of Glaciology*, doi:10.1017/jog.2017.80.

Ziemen, F. A., R. Hock, A. Aschwanden, C. Khroulev, C. Kienholz, A. Melkonian, and J. Zhang (2016), Modeling the evolution of the Juneau Icefield between 1971 and 2100 using the Parallel Ice Sheet Model (PISM), *Journal of Glaciology*, *62*(231), 199–214.

Chapter 3: Nearshore marine conditions in summer controlled by glacier runoff in Juneau, Alaska[2]

3.1 Abstract

Glaciers in the mountainous headwaters of high latitude coastal environments have numerous influences on adjacent terrestrial and aquatic ecosystems. As temperatures continue to warm, these glaciers are projected to continue losing mass at high rates, with consequences for the timing, magnitudes, and composition of freshwater delivery downstream. The extent to which glacier runoff controls oceanographic conditions in the nearshore marine environment is uncertain, as is knowledge of whether changes to the former can be detected in the latter. This study examines 1980 to 2016 partitioning and trends of modeled hydrological variables for the Mendenhall Glacier watershed near Juneau, Alaska, which we take to represent typical regional patterns of freshwater discharge from glacierized basins draining into Lynn Canal. We compare model simulations from the coupled modeling tool SnowModel-HydroFlow to observed oceanographic conditions at a nearshore marine monitoring site at Auke Bay in Lynn Canal. We find that in May through September, the upper 10 to 15 m of the ocean water column is substantially fresher (10 to 30 PSU) and less dense (1010 to 1023 kg m^{-3}) than standard sea water ($\sim$35 PSU and $\sim$ 1025 kg m^{-3}). Glacier runoff sampled and averaged over the seven days prior to each CTD measurement shows robust correlation to salinity ($r^2 = 0.66$, $p \ll 0.001$) and density ($r^2 = 0.68$, $p \ll 0.001$) averaged over the uppermost 5 m of the water column. It also correlates more strongly than either total runoff or glacier ice melt, indicating that freshwater that is sourced from or has been modified by glaciers exerts the dominant control over the nearshore environment of the terrestrial hydrological variables. However, water temperature in the upper 10 to 15 m appears to be more

[2]Young, J.C., Pettit, E., Hood, E., and A. Arendt (2020). *Nearshore marine conditions in summer controlled by glacier runoff in Juneau, Alaska.* Manuscript in preparation.

strongly influenced by air temperature than by glacier runoff, as indicated by strong positive correlations between water column and air temperature ($r^2 = 0.73$, $p \ll 0.001$). Nonetheless, on measurement dates associated with the highest inputs of glacier runoff, temperatures in the uppermost 2 to 5 m abruptly decrease by several degrees Celsius, an indication of a dominant glacier runoff lens despite warm air temperature influences. Finally, we detect decreasing trends from 1997 to 2016 in mean salinity of the upper 5 m of the water column in most months. The decrease is most statistically robust and largest in August ($p = 0.01$, -3.2 PSU), aligning with detection of a large trend in August glacier runoff amounts ($p = 0.02$, 15%) from the modeled period of 1980 to 2016. This study is among the first to directly link terrestrial hydrological processes in glacierized watersheds to oceanographic conditions in the nearshore marine environment via a distributed, high temporal resolution glacio-hydrological model. Overall, this study finds that glacier runoff controls water column stratification within the nearshore environment in Lynn Canal, and confirms that changes are underway to that structure, with consequences for marine organisms that occupy these depths.

3.2 Introduction

Bounded by topography that extends from sea level to >5000 m a.s.l., and with a maritime climate characterized by between 2 to 8 m w.e. of snow and rain per year [*Daly et al.*, 2008], the Gulf of Alaska (GOA) watershed is defined by extensive glacier cover as well as very large volumes of freshwater runoff. Whereas other major watersheds in North America primarily drain via large rivers, ∼80% of Gulf of Alaska runoff arrives at the coast via short (∼10 km average), steep, small drainages [*Neal et al.*, 2010]. Moreover, along the Gulf of Alaska, glacier ice often lies directly adjacent to the forested areas of the northern Pacific temperate rainforest. Together, these unique characteristics create a tight coupling between ice and snow melt from alpine terrain and the downstream marine ecosystem.

Given this strong linkage between the terrestrial and nearshore domains, the presence of glaciers plays a crucial role in both the hydrology and ecology of the Gulf of Alaska region [*O'Neel et al.*, 2015]. In terms of hydrological influences, glaciers act as a frozen freshwater reservoir, temporarily storing water over short-term (daily), intermediate (seasonal) and longer-term (decadal to centuries-long) time spans [*Jansson et al.*, 2003]. Drainages containing as little as 5% glacier cover by area demonstrate distinct flow patterns compared to their ice-free counterparts, with delayed peak runoff that corresponds with peak air temperatures in mid-summer, and with decreased annual and monthly variability [*Fountain and Tangborn*, 1985]. Streamflow measurements downstream of glaciers experiencing persistent negative net mass balance also display a pattern characterized initially by increased flow due to higher rates of mass loss, followed by decreased runoff due to overall glacier volume loss [*Jansson et al.*, 2003].

Zooming out to the regional scale, runoff from glaciers, which comprise 87,000 km^2 or ~18% of the Gulf of Alaska watershed [*Kienholz et al.*, 2015], makes up nearly half (38 to 47%) of the annual freshwater input into the Gulf of Alaska, of which 7 to 10% of the freshwater input is attributed to glacier volume loss in recent studies [*Neal et al.*, 2010; *Hill et al.*, 2015; *Beamer et al.*, 2016]. This freshwater input maintains a density gradient that acts as a principal driver of the Alaska Coastal Current, a nearshore current that delivers nutrients and establishes broad salinity patterns along the entire Gulf of Alaska coast [*Royer*, 1981].

Glacier runoff (i.e. from melted glacier ice or from terrestrial water that has passed through a glacier and inherited the associated biogeochemical characteristics) has numerous other influences on the function of downstream terrestrial and aquatic ecosystems. First, glacier runoff possesses physical attributes like temperature and turbidity that are unique relative to rain or snowmelt [*Hood and Berner*, 2009; *Fellman et al.*, 2014]. Glacier runoff also influences fluxes of limiting nutrients such as phosphorus, nitrogen and iron [*Hood et al.*, 2009; *Crusius et al.*, 2011] and bioavailable organic carbon [*Hood et al.*, 2009]. Even small glacierized drainages have been found to yield high nutrient and sediment loading to the greater coastal oceans [*Destouni et al.*, 2008].

In glacier-influenced nearshore marine environments, glacier runoff plays a role in biological productivity at all trophic levels, beginning with primary productivity, i.e. the production of organic compounds from carbon dioxide. From carbon stable isotope analysis, ancient glacier-sourced organic carbon has been traced through the proglacial riverine food web first by uptake into biofilm (bacterial aggregates that form on rocks and river bottoms) to macroinvertebrates to juvenile salmonids [*Fellman et al.*, 2015]. *Arimitsu et al.* [2016] found that phytoplankton abundance in several Alaska fjords with tidewater glaciers and glacial rivers in their headwaters could be explained by physical gradients and nutrient availability resulting from the input of glacier-sourced freshwater. The same study also found that copepod and fish distribution were related to the same gradients, and that the distribution of seabirds was in turn explained by the availability of those prey species. Seals and whales have similarly been found to congregate around tidewater glacier fjord feeding hotspots, particularly where plankton and fish are entrained in freshwater upwelling at the glacier terminus [*Lydersen et al.*, 2014]. Several studies have examined the influence of glacier runoff on salinity and temperature patterns of water within fjords. *Arimitsu et al.* [2016] found that gradients in temperature, salinity, and turbidity were observed up to 10km from the glacier outlet in several Alaska glacierized fjords. Other field-based studies in Alaska have used oceanographic measurements to detect the existence of a cold, fresh, and sediment-laden upper layer in the water column due to buoyancy of relative low density glacier runoff-modified water atop higher density seawater in glacier fjords [*Motyka et al.*, 2003; *Etherington et al.*, 2007; *Bartholomaus et al.*, 2013]. However, little research to date has directly linked high temporal resolution freshwater fluxes from a terrestrial glacio-hydrological model to downstream measurements of nearshore marine conditions, as studies typically infer freshwater input into glacier fjords through physical oceanographic measurements.

In this study, we analyze simulations from the coupled energy balance and hydrological routing model SnowModel-HydroFlow that describe on a daily time step all components of the freshwater balance for a well-monitored glacierized drainage originating in the Juneau Icefield and discharging freshwater into Lynn Canal, Southeast Alaska. We carried out simulations for a domain encompassing the full Juneau Icefield watershed as part of a separate study on long-term runoff trends in the region [*Young et al.*, 2020 – in review]. These simulations were calibrated to field and airborne datasets including Juneau Icefield-wide glacier mass balance estimates and long-term stream gauge data, and validated against regional mass changes derived from satellite gravimetry data. For this study, we sample model output fields for all terrain above the mouth of the Mendenhall River, and assess the partitioning of different components of freshwater entering the ocean. We also examine trends in these quantities, to determine which contributions have been changing over the period of study. Finally, we compare model output to oceanographic observations from a repeat measurement site in Auke Bay, a small inlet on the eastern side of Lynn Canal, located approximately 1 km from the Mendenhall River outflow. Though we analyze hydrological output from one drainage and oceanographic observations at a specific marine location, we analyze both datasets as regionally representative, for reasons we explain in Section 3.7. Altogether this study aims to examine the strength of the linkage between terrestrial glacio-hydrological processes and nearshore marine conditions at high temporal resolution.

3.3 Study area & previous work

Centered at 58.9260° N and 134.2411° W, the Juneau Icefield spans the Coast Mountains between Southeast Alaska, USA and northwestern British Columbia, Canada (Fig. 3.1). The icefield has an area of <3700 km^2 and elevation range from sea level to ∼2300 m a.s.l [*Kienholz et al.*, 2015], and snow and/or ice melt occurs over the full extent during the summer months [*Ramage et al.*, 2000]. The icefield also experiences a strong precipitation gradient from southwest to northeast (i.e. approximately with increasing distance from the coast), as evidenced in ground observations [*Pelto et al.*, 2013], as well as in a recent volume change study by *Ziemen et al.* [2016] and an orographic precipitation modeling study by *Roth et al.* [2018]. In particular, as it lies directly in the path of southwesterly cyclonic storms originating in the Gulf of Alaska and striking the coast [*Stabeno et al.*, 2004], the western portion of the icefield endures one of the wettest climates in North America [*Shulski and Wendler*, 2007]. Moreover, as temperatures frequently hover near the freezing point on the coast [*Shulski and Wendler*, 2007], low elevations may see rain and/or snow- and ice melt throughout the year.

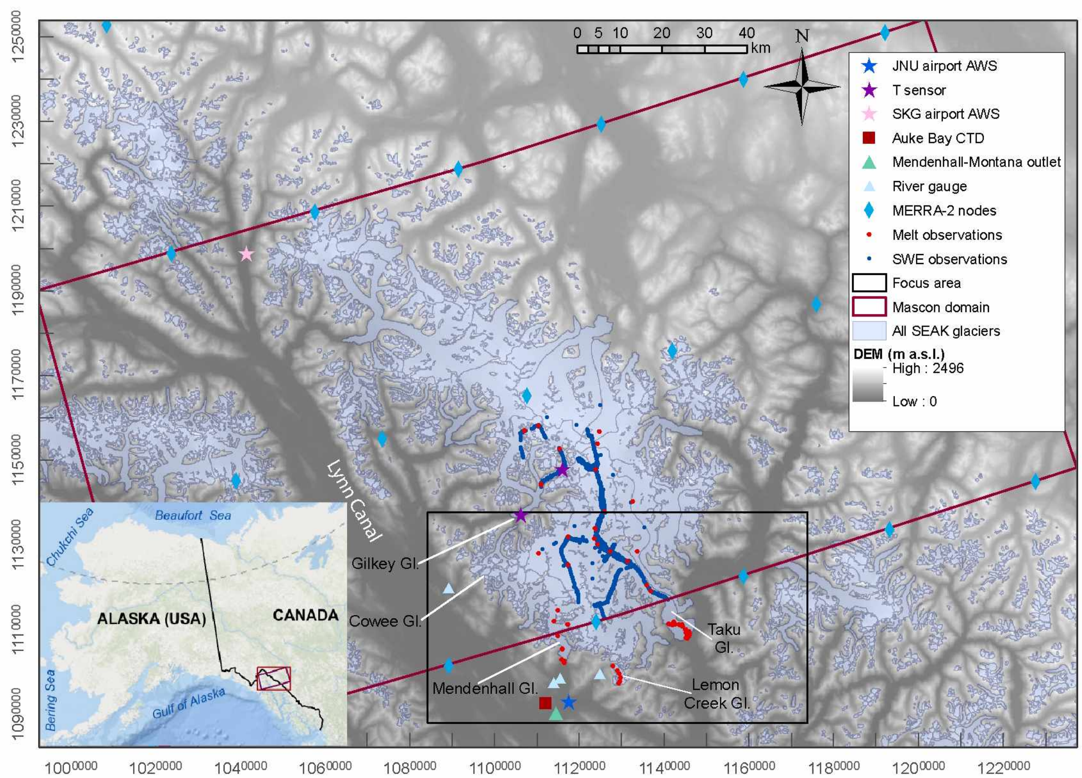

Figure 3.1: Location of the Juneau Icefield within the Coast Mountains spanning southeast Alaska and northern British Columbia. All glaciers within the full model domain are shown in light blue. Also shown are: locations of automated weather stations at each the Juneau (JNU) and Skagway (SKG) airports; MERRA-2 reanalysis climate nodes; the mascon domain showing the area of GRACE solutions used for model validation; campaign on-ice temperature sensors; observations of melt and snow water equivalent; the Mendenhall-Montana outlet location; and river gauge stations. The spatial extent of this figure denotes the full domain used for model calibration and validation, while the black box outlines the focus area of our analyses, as shown in Figure 3.2.

The Mendenhall Glacier is located on this western side of the icefield and experiences this high latitude maritime climate (Fig. 3.2). At ~25 km long and ~125 km^2 in size, the Mendenhall flows west from an ice divide at ~1860 m a.s.l. to its terminus at a 95 km^2 proglacial lake at 20 m a.s.l. Surrounding topography within the full drainage extends from the mouth of the Mendenhall River at sea level to the outflow of the proglacial lake ~7 km upstream, and to ~1980 m a.s.l. at the summit of surrounding peaks. In total, glacier ice covers 43.7% of the 290 km^2 drainage above the ocean outflow point, and 56.3% of the 223 km^2 area above the location of a long-term stream gauge location (Section 3.4.3).

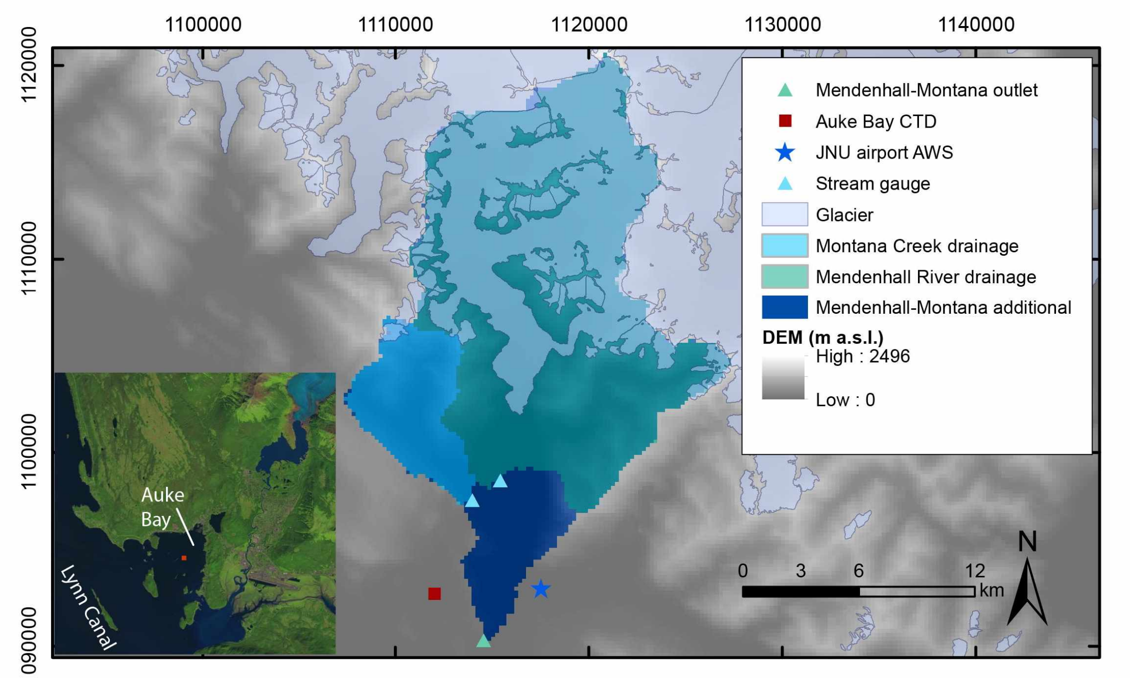

Figure 3.2: Map of the Mendenhall Glacier and watershed, with field dataset locations. Shown are river gauges, location of the Mendenhall-Montana river outlet, Auke Bay oceanographic monitoring site, and NOAA AWS at Juneau airport. The inset shows a false-color LandSat 8 image of the Mendenhall terminus, proglacial lake, and river, as well as the location of the Auke Bay monitoring site.

Several studies have derived mass loss rates for different time periods for Juneau Icefield glaciers. *Motyka et al.* [2003] estimated a volume loss of the glacier of 5.5 km^3 between 1948 and 2000. *Boyce et al.* [2007] calculated glacier-wide mass balance rates using field-based glaciological methods ranging from as high as +1.4 to as low as -1.8 m w.e. a^{-1} between

1998 and 2005. Several recent studies have also used geodetic approaches to estimate bulk volume loss between two satellite image dates for the Juneau Icefield as a whole. Despite sourcing imagery from different satellite sensors and covering different time spans, all studies calculated negative glacier-wide mass balance rates over the investigated periods between 1962 to 2016 [*Larsen et al.*, 2007; *Berthier et al.*, 2010; *Melkonian et al.*, 2014; *Berthier et al.*, 2018]. Most recently, *Berthier et al.* [2018] used imagery from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) to derive a mass balance rate of -0.68 ± 0.15 m w.e. a^{-1} for 2000 to 2016, a value that agrees closely with laser altimetry approaches and is therefore taken as the current best estimate. Within that study, the mass balance rate for the Mendenhall Glacier in isolation was calculated at -0.73 ± 0.13 m w.e. a^{-1} for the same time period, a close match to the mean for the icefield as a whole. Looking to the future, a dynamical modeling study by *Ziemen et al.* [2016] projected a volume loss of 56 to 68% of the current volume of the icefield by 2100 under different climate scenarios.

Runoff from the western portion of the Juneau Icefield travels from alpine to estuary via short, steep rivers characteristic of Southeast Alaska drainages [*Neal et al.*, 2010] and into Lynn Canal, a 5-to-15 km wide saltwater arm that together with Chatham Strait can be considered a 380 km long ice-carved fjord [*Martin and Williams*, 1924]. While Lynn Canal no longer has contributions of glacier meltwater from tidewater glacier termini in direct contact with ocean water, the glacially-fed rivers draining into the canal show strong biogeochemical (e.g. dissolved organic carbon, nitrogen, and phosphorous) [*Hood and Berner*, 2009; *Hood and Scott*, 2008] and physical (e.g. water temperature) [*Fellman et al.*, 2014] differences relative to their non-glacierized counterparts. Moreover, this influence extends downstream beyond the river corridor, for example as a major source of dissolved organic matter in the nearshore marine environment [*Fellman et al.*, 2010; *Hood et al.*, 2009]. The degree to which this influence extends into the broader Lynn Canal remains uncertain.

Overall, the Juneau Icefield and surrounding area are among the best-monitored regions in Alaska in terms of glacier mass balance monitoring, hydrological observations (see Section

3.4.3), and riverine and nearshore marine biogeochemistry and ecology studies. Altogether, this rich context compels our choice of this location for our study.

3.4 Data & methods

To estimate glacier mass loss and total runoff for the Mendenhall Glacier basin for Oct. 1, 1980 to Sept. 30, 2016, we leverage simulations from a study that modeled runoff from both glacier and land surfaces for a larger watershed encompassing the full western drainage of Southeast Alaska's Juneau Icefield [*Young et al.*, 2020 – in review]. We generated these simulations using the snow distribution and evolution model SnowModel [*Liston and Elder*, 2006a] coupled with both the SoilBal routine for calculating evapotranspiration over ice-free terrain [*Beamer et al.*, 2016] and the linear reservoir runoff routing model HydroFlow [*Liston and Mernild*, 2012]. The model routines are described briefly below, as are the data and approaches that were used for calibration and validation. The simulations used a daily time step and a grid cell resolution of 200 x 200 m, chosen as a compromise between desired spatial resolution and computational efficiency. Model simulations were carried out over an extended spatial domain (Fig. 3.1), in order to leverage calibrating datasets available at broader spatial scales than within the Mendenhall River drainage.

For comparison of our modeling results to oceanographic data, we leverage observations of ocean salinity, temperature, and density as described below.

3.4.1 SnowModel-HydroFlow model description

The distributed energy balance model SnowModel is designed for terrain and climates where snow and ice are present [*Liston and Elder*, 2006a]. SnowModel and associated sub-routines use meteorological, terrain, and surface type data to account for all processes involved in the evolution of the snowpack including: snow accumulation; forest canopy interception, unloading, and sublimation; snow-density evolution; and snowpack and ice melt. SnowModel is comprised of several integrated sub-routines. 1) MicroMet is a quasi-physically-based data assimilation and interpolation routine that defines spatially distributed climate forcing for SnowModel simulations based on the digital elevation model (DEM) for the model domain [*Liston and Elder*, 2006b]. 2) EnBal calculates the surface energy exchange at every grid cell in response to the atmospheric conditions produced by MicroMet. Energy flux calculations at the ice- and snow-atmosphere interfaces include standard energy balance components such as latent and sensible heat and incoming solar radiation, and any surplus energy is assumed to be available for melt. 3) SnowPack simulates snow depth and the snow water equivalent evolution within the snowpack, based on both precipitation and melt processes. Snow density evolves as a result of the weight of overlying snow, temperature changes, and meltwater generation and percolation through the snow column. Further detail on both EnBal and SnowPack can be found in *Liston and Elder* [2006a].

Note that SnowModel does not include a glacier flow model for glacier mass redistribution. To avoid continuous snow accumulation at high elevations during multi-year simulations, each year's end-of-summer snow pack is reset to zero based on the assumption that all residual snow is converted to glacier ice. This practice is typical of other glacier mass balance modeling studies (e.g. *Beamer et al.* [2016]; *Young et al.* [2018]). SnowModel also does not account for changes to glacier hypsometry (area-altitude distribution) by thinning or ice flow, or to glacier area by retreat. Instead, a constant surface representing conditions at a reference year/time is maintained throughout the simulation. This reference surface approach may contribute to uncertainty in our estimates of cumulative mass balance over time [*Elsberg et al.*, 2001].

In addition to SnowModel, two other modules are coupled in the workflow in *Young et al.* [2020 – in review]. SoilBal, a soil moisture submodel, enables full water balance calculations in vegetated landscapes by accounting for evapotranspiration [*Beamer et al.*, 2016]. SoilBal calculates potential evapotranspiration by use of the Priestley-Taylor equation [*Priestley et al.*, 1972], a standard evapotranspiration formulation successful at reproducing observed evapotranspiration in forested landscapes [*Komatsu*, 2005]. SoilBal calculates soil water balance from inputs of potential evapotranspiration, SnowModel runoff, and gridded soil water storage principally based on soil type information from *Fischer et al.* [2008]. Remaining surface and base flow runoff are summed and passed to the module HydroFlow.

HydroFlow simulates the routing of immediately available surface runoff from rain, snow, and ice melt in each grid cell over the landscape [*Liston and Mernild*, 2012]. In HydroFlow, each grid cell acts as a linear reservoir that transfers water from itself and upslope cells to the downslope cell, creating a topographically linked flow network. In every grid cell, HydroFlow applies two transfer functions with time scales associated with different slow and fast water routing mechanisms, such as water transport through snow versus surface streamflow. HydroFlow assigns different residence time coefficients and velocities for four principal surface types: snow-covered ice, snow-free ice, snow-covered land, and snow-free land. A coupled system of equations solves for slow- and fast-response flow, and yields a discharge hydrograph for each grid cell.

3.4.2 Model input data

The simulations utilized a DEM from the USGS National Elevation Dataset (https://nationalmap.gov/elevation.html) at a resolution of 1 arcsec (∼30 m) where available, and 2 arcsecs (∼60 m) elsewhere (over portions of Canada). The DEM represents elevations from the early 2010s, and is hydrologically corrected (i.e. depressionless). Land cover classes were obtained from the North American Land Change Monitoring System (http://www.cec.org/tools-and-resources/map-files/land-cover-2010-landsat-30m), which distinguishes classes of vegetation, bare land, and urbanized area for North America at a 30 m resolution [*Homer et al.*, 2015]. The grid was reclassified to the categories defined in *Liston and Elder* [2006a], as well as updated with more accurate glacier outlines from the Randolph Glacier Inventory v6.0 (https://www.glims.org/RGI/rgi60_dl.html) [*Pfeffer et al.*, 2014; *Kienholz et al.*, 2015]. Soil types were classified using the gridded Harmonized World Soil dataset version 1.2 (http://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/harmonized-world-soil-database-v12/en/), available at a 1 km resolution [*Fischer et al.*, 2008]. All grids were resampled from their native resolutions to the model resolution of 200 m.

SnowModel requires as input spatially and temporally continuous variables of daily temperature, relative humidity, precipitation, and wind speed and wind direction. Reanalysis data were acquired from NASA's Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2) [*Gelaro et al.*, 2017] (https://gmao.gsfc.nasa.gov/reanalysis-/MERRA-2/data_access/). This product was chosen given that Version 1 of MERRA was found in a freshwater modeling study for the Gulf of Alaska watershed to outperform several reanalysis products in reproducing measurements of point glacier mass balance and local domain streamflow [*Beamer et al.*, 2016]. It was also found in a comparison of reanalysis products over the Arctic to be most consistent with measured 2 m air temperature and precipitation [*Lindsay et al.*, 2014], variables especially important for modeling glaciers and snow. Moreover, snow amounts from MERRA-2 have a lower bias and better correlation than MERRA-1 to reference data in neighboring parts of Canada [*Reichle et al.*, 2017].

3.4.3 Model calibration

In order to correctly reproduce both glacier mass balance as well as freshwater discharge, a two-stage approach to model calibration was used as described in [*Young et al.*, 2020 – in review]. The first stage leveraged an automated step within SnowModel, which uses a data assimilation scheme called SnowAssim to compile and interpolate all available observations of snow water equivalent (SWE) [*Liston and Hiemstra*, 2008]. SnowAssim calculates differences between observed and modeled SWE values, and applies multiplicative corrections either to precipitation values or melt factors in order to retroactively create more realistic distributions of SWE prior to the observations. Point observations of SWE used to drive SnowAssim were obtained from several sources as shown in Fig. 3.1 and described in [*Young et al.*, 2020 – in review], including data from our own field campaigns, available at *Young* [2019]. Ground-penetrating radar snow depth observations were also collected and converted to SWE values by USGS along the Taku Glacier [*McGrath et al.*, 2015] and Gilkey Glacier centerlines in spring 2014 and 2015, in collaboration with our field campaigns [*O'Neel et al.*, 2018].

For the second calibration stage, *Young et al.* [2020 – in review] employed a traditional grid search approach to model parameter tuning. Focusing on glacier albedo, melting (non-forested) snow albedo, monthly precipitation lapse rates, monthly temperature lapse rates, and the factor for modifying the fast reservoir velocity in HydroFlow, a broad range across the parameter space was first tested before honing in on a narrower range. Next, model performance was evaluated using independent calibration datasets, including a geodetic estimate of glacier volume loss from *Berthier et al.* [2018] for the full Juneau Icefield between 2000 and 2016, a value that translates to -0.68 $\pm$ 0.15 m w.e. a^{-1}. Of our over 200 model simulations, an ensemble of 16 simulations with mass balance rates was found to lie within the limits of uncertainty of that estimate for the equivalent time period.

For all simulations in that ensemble, HydroFlow output of discharge (Q) was next compared to streamflow data for four gauged drainages. A semi-continuous time series of discharge data is available for three streams from the United States Geological Survey (USGS) (Mendenhall River, Lemon Creek, and Montana Creek; data available at https://waterdata.-usgs.gov/nwis/rt) and one monitored by researchers at the University of Alaska Southeast (Cowee Creek) (Fig. 3.2). The calibration approach aimed to reproduce monthly simulated discharge to observed discharge for all upstream terrain as routed to the gauge locations, seeking out Nash-Sutcliffe Efficiency values [*Nash and Sutcliffe*, 1970] and coefficient of determination (r^2) values nearest to 1. For calibration, model output in the Mendenhall watershed was extracted for all terrain above the location of the stream gauge. All final analyses and interpretation, unless otherwise stated, encompass the full Mendenhall watershed above its outflow to the coast.

Finally, model output was compared to point observations of melt (snow or ice) from the above-mentioned field campaigns, though these statistics were relatively insensitive to changes after the first automated calibration step (SnowAssim). In the end, this process

Table 3.1: Calibration parameters for SnowModel-HydroFlow simulations. Columns show: 1) Parameter name/symbol, 2) Description of parameter, 3) Range of values tested, and 4) Final value. Note that the bottom portion of the table lists a selection of prescribed parameters that are not varied.

1) Parameter	2) Description	3) Value/range tested	4) Final value
α_{ice}	Glacier ice albedo	0.05 to 0.65	0.30
$\alpha_{\mathrm{snow\_melt\_clear}}$	Non-forested (clearing) melting snow albedo	0.15 to 0.70	0.50
Γ_{low}, Γ_{high}	Monthly varying temperature lapse rate	Jan/June low: 2.4/6.2, Jan/June high: 6.4/10.2°C km^{-1}	Jan/June: 3.9/7.7°C km^{-1}
χ_{low}, χ_{high}	Monthly varying precipitation lapse rate	Jan/June low: 0.20/0.05, Jan/June high 0.50/0.35 km^{-1}	Jan/June: 0.20/0.05 km^{-1}
$\mathrm{f_f}$	Factor for fast response time; channel flow	0.05 to 2.0	0.25
$\alpha_{\mathrm{snow\_fresh}}$	Fresh snow albedo	0.75 to 0.98	0.75
$\alpha_{\mathrm{snow\_melt\_forest}}$	Forested melting snow albedo	—	0.45
$\mathrm{T_{rain}}$, $\mathrm{T_{snow}}$	Threshold rain/snow temperatures	—	0°C, 2°C
$\mathrm{f_s}$	Factor for slow response time; matrix flow	—	0.05

yielded an ensemble of simulations among which a midpoint ensemble member most closely matched the goal value from *Berthier et al.* [2018], i.e. with $\dot{B}_{\mathrm{diff}} = 0$, and which we use for the bulk of our analyses. Two additional ensemble end members whose trends correspond to the upper and lower limit of the *Berthier et al.* [2018] estimate error bars are used as upper and lower estimates of uncertainty.

The SnowModel-SoilBal-HydroFlow distributed model suite employs a large number of parameters. A selection of our tested ranges and final parameter values, as well as select default values, are highlighted in Table 3.1. A more complete table of parameter descriptions and values can be seen in *Young et al.* [2020 – in review].

3.4.4 Model validation

Model results were validated by comparison to a time series of terrestrial water changes for the Juneau Icefield area derived from the independent data source GRACE. The tandem GRACE satellites, launched in 2003, use a K-band inter-satellite ranging system to detect changes in local gravity fields resulting from mass variations. To isolate terrestrial changes only, forward-modeling is used to remove time-varying gravity signals from Earth tides, ocean tides and atmospheric loading (i.e. clouds) [*Wouters et al.*, 2014], such that the remaining signal represents the full terrestrial water budget, i.e. snowfall, rain and runoff from non-glacierized and glacierized terrain, including glacier ice melt. GRACE data boast a high temporal resolution (∼30 days) relative to e.g. geodetic glacier mass balance methods, and no density assumptions are required to account for changes in snow and ice volume, eliminating a prominent source of uncertainty. However, known issues with GRACE data include a coarse spatial resolution (1° x 1°, or ∼12,390 km^2) and the potential for signal bleed across adjacent grid cells, a processing artifact [*Luthcke et al.*, 2013].

GRACE data were acquired from NASA Goddard Space Flight Center Geodesy Laboratory's high resolution v2.4 mass concentration (mascon) solution [*Luthcke et al.*, 2013]. The analysis method for this product is described in *Loomis and Luthcke* [2014]. This dataset was chosen because it is among few that corrects for local mass increases associated with post-Little Ice Age disintegration of the Glacier Bay icefield [*Larsen et al.*, 2005]. It also compares well with regional-scale mass balance model simulations for the glacierized Gulf of Alaska watershed [*Hill et al.*, 2015; *Beamer et al.*, 2016] and to mass loss estimates from NASA's Ice, Cloud and Land Elevation Satellite (ICESat) [*Arendt et al.*, 2013]. The focus area for model validation was the two-mascon domain containing the Icefield, as seen in Figure 3.1.

3.4.5 Oceanographic data

To assess the direct link between glacier runoff and nearshore marine conditions downstream, we obtain data from the Southeast Alaska Coastal Monitoring program, a National Oceanographic and Atmospheric Administration (NOAA) juvenile salmon monitoring effort in Southeast Alaska. As part of the effort, measurements of salinity, temperature, and density are collected by conductivity/temperature/depth (CTD) casts, carried out once per month between May and August each year since 1997. Annual reports are available at http://www.npafc.org (e.g. *Fergusson et al.* [2018]). One of the monitoring program's recurrent measurement sites is located in Auke Bay (58°22' latitude and -134°40' longitude), 0.5 km from shore and ~1 km adjacent to the Mendenhall River outlet. CTD casts are conducted using a Sea-Bird SBE 25 Profiler deployed to within 10 m of the ocean bottom (i.e. a depth of 60 m in Auke Bay), at 1 m spacing [*Fergusson et al.*, 2018]. For our analysis, measurements of salinity, temperature, and density are averaged from 0 to 5 m depths. We chose this depth based on examination of the vertical profiles, which indicated this is the most dynamic stratum of the water column.

For correlating our hydrological variables to the oceanographic measurements, we averaged the modeled variables over the seven days leading up to and including the CTD measurement date. Preliminary analysis of different averaging windows between one to 14 days revealed that correlation strength grew with the length of the averaging window. However, we chose the seven-day window as a compromise between employing too long of an averaging window that risked smoothing out high and low hydrological input events, while still allowing for lag time between runoff outflow and circulation to the Auke Bay monitoring site. Because a peninsula and a series of small islands act as a barrier to direct circulation from the river outlet to the Auke Bay site (Figure 3.2), we consider the oceanographic measurements to represent more of a regional reading of Lynn Canal oceanographic conditions than the result of Mendenhall River output alone. Similarly, we regard our modeled Mendenhall drainage outflow as representative of regional glacio-hydrological input into Lynn Canal. We believe this to be a reasonable assumption given that the mass loss rate for the Mendenhall Glacier closely matches the mean for the full Juneau Icefield (-0.73 $\pm$ 0.13 m w.e. a^{-1} vs -0.68 $\pm$ 0.15 m w.e. a^{-1}), whereby the icefield feeds drainages that deliver freshwater along the full eastern side of Lynn Canal.

3.4.6 Trend detection and correlation

To detect trends within the different modeled hydrological and measured oceanographic variables, we employ the Mann-Kendall test for significance. This is a non-parametric test (i.e. data do not have to meet the assumption of normality). Trends themselves are calculated using the non-parametric Theil-Sen estimator. Because it is more robust against outliers than simple linear regression, this approach is commonly used in hydrological applications [*Helsel and Hirsch*, 2002]. We report for each model trend a harmonic mean p-value, a formulation for combining p-values from tests that cannot be guaranteed to be independent [*Wilson*, 2019], such as model simulations with variation in parameter values but not in model physics. We equally weigh our midpoint and two end member simulation p-values in calculating each harmonic mean p-value. For trend detection tests in oceanographic variables, we report a single p-value given a lack of reported error.

In reporting our findings, we additionally include a measure of effect size (i.e. trend as a percent change relative to the original value) as well as confidence intervals, i.e. trends derived from our simulation end members. These measures provide additional information for interpreting each trend detection test as meaningful, given recent literature that challenges the traditional notion that a p-value $\leq$0.05 is the sole determinant of a significant or non-significant result (e.g. *Halsey* [2019], *Amrhein et al.* [2019]). Together, these statistics provide additional insight into the range of possibilities that are reasonably likely for each trend.

Tests for correlation between variables are all conducted using simple linear regression. Here too, we report harmonic mean p-values for statistical significance, and the r^2 value for our midpoint model simulation as a measure of effect size.

3.5 Model performance

Our modeled, tuned glacier-wide mass balance rate for 2000 to 2016 for the Mendenhall Glacier is -0.73 m w.e. a^{-1}, which matches the estimate of -0.73 $\pm$ 0.13 m w.e. a^{-1}

from *Berthier et al.* [2018]. Our mass balance rate for the Juneau Icefield in its entirety also matches the estimate from *Berthier et al.* [2018] (as was the goal of our calibration efforts) at -0.68 a^{-1} with lower and upper uncertainty bounds of -0.57 and -0.83 m w.e. a^{-1} corresponding to our simulation ensemble end members.

Our model simulations also compare well against other calibrating datasets. Our initial calibration routine SnowAssim improves correlation between modeled and observed point SWE estimates from field and airborne campaigns from $r^2 = 0.45$ and RMSE = 0.45 m w.e. to $r^2 = 0.90$ and RMSE = 0.18 m w.e. This highlights the utility of the SnowAssim routine for producing more realistic SWE fields. The model also reproduces point snow/ice ablation observations well, yielding $r^2 = 0.79$ and RMSE = 1.63 m w.e. The larger RMSE values are expected given that measurements were primarily made in lower ablation areas, which on large glaciers can display substantial local variability due to ice surface topography that may not be captured by the model.

Figure 3.3 shows modeled versus observed discharge for the Mendenhall River above the gauge location. Overall, the model's ability to reproduce stream gauge observations for the four instrumented basins used in our calibration scheme varies. For the two basins with the highest percent glacier cover, comparison of modeled to observed monthly discharge yields strong agreement. For the Mendenhall River (56% glacier cover above the gauge), we find NSE = 0.84 and $r^2 = 0.88$, and for Lemon Creek (46% glacier cover), we obtain NSE = 0.76 and $r^2 = 0.82$. For the two basins that are predominantly forested, modeled to observed agreement is weaker: for Montana Creek (2% glacier cover), we find NSE = -1.37 and $r^2 = 0.45$, and for Cowee Creek (11% glacier cover), we obtain NSE = -0.81 and $r^2 = 0.47$. Altogether, weighing all four basins by both area and length of measurement record, we obtain a weighted NSE = 0.21 and $r^2 = 0.73$.

We note that the model does not reproduce many of the large peaks in the Mendenhall discharge record. Several of these are associated with recent (2011 and on) glacier lake outburst floods from an upstream tributary, a type of impulsive event for which the model

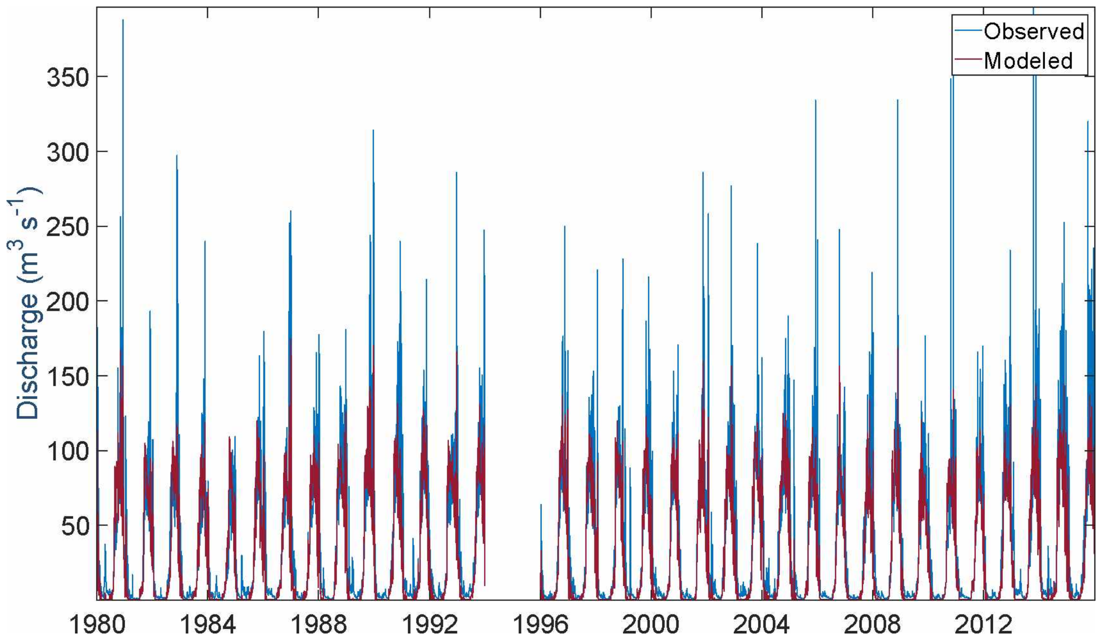

Figure 3.3: Time series of modeled versus observed discharge Q at the Mendenhall River gauge between 1980 to 2016.

has no mechanism. The difficulty in reproducing other large peaks appears to be due to seasonal bias between modeled and observed quantities. This mismatch is evident primarily as an overproduction of discharge in spring and an underproduction in summer. This may be explained by the finding that MicroMet-interpolated MERRA-2 air temperature fields are generally warmer in spring and colder in summer than observations, thereby generating too much and too early snow melt in spring, and too little glacier ice melt in summer. This is consistent with a comparative study of reanalysis products for hydrological applications by *Wrzesien et al.* [2019]. The authors found that for several major watersheds in North America, MERRA-2 does not maintain snow in mountainous terrain late enough into spring, which they surmised was likely due to both precipitation biases and warm temperatures.

Overall, streamflow represents an integration of all glacio-hydrological processes in the watershed, and can therefore be the most challenging to replicate. Nonetheless, the model shows strong statistical performance in reproducing monthly streamflow in the Mendenhall drainage above the gauge location which, as our focus area, lends confidence to our results. Moreover, as our model performs well in reproducing other calibration datasets related to glacier mass balance, a primary focus of our study, we believe our model performance to be reliable.

In terms of validation, for the 2003 to 2016 period overlapping with GRACE data availability, we calculate a glacier-wide mass balance rate for all ice cells within the equivalent GRACE domain of -0.51 [-0.18, +0.13] m w.e. a^{-1} (or -2.5 [-0.9, +0.6] km^3 a^{-1}), in close agreement with the GRACE-derived negative trend estimate of -0.55 m w.e. a^{-1} (-2.7 km^3 a^{-1}). Correlation between these two time series is robust; our model explains 91% of the variance in the GRACE time series ($p \ll 0.001$).

However, in comparing GRACE to modeled results for ice and land cells together, we observe that correlation is less strong ($r^2 = 0.36$, $p \ll 0.001$), given a mismatch in the modeled long-term trend (i.e. domain-wide mass balance rates), which is not sufficiently negative at -0.002 m w.e. a^{-1}. Because we expect a strong overall water storage loss due to glacier volume loss in this region, and given that we do not expect substantial gains in terrestrial water balance over land cells, this indicates that SnowModel is producing too much precipitation over land cells in our domain, resulting in a positive water balance over terrestrial cells (0.12 m w.e. a^{-1}). Nonetheless, our full SnowModel land+ice water balance produces seasonal amplitudes (mean annual accumulation = 25.8 km^3 a^{-1}, ablation = -26.6 km^3 a^{-1}) that are more consistent with those from GRACE (18.1 and -21.5 km^3 a^{-1}) than those from ice cells alone (9.0 and -12.1 km^3 a^{-1}). This result is encouraging as the GRACE solution measures all components of the terrestrial water balance. It also aligns with recent studies for the Gulf of Alaska watershed [*Beamer et al.*, 2016] and the Canadian Arctic Archipelago [*Lenaerts et al.*, 2013], in which seasonal amplitudes from GRACE solutions could only be reproduced by summing together modeled mass changes over both glacierized and ice-free regions of the domain. Altogether, the results of this independent validation highlight the model's ability to reproduce the meso- and synoptic-scale climatic processes over the ice-covered portions of the domain, in line with our goal to analyze model output for the Mendenhall Glacier as regionally representative of terrestrial water storage changes.

3.6 Results

3.6.1 Increasing glacier runoff and ice melt contributions

For the period 1980 to 2016, our model yields a mean annual runoff volume of 1.28 ± 0.02 km^3 a^{-1} from the Mendenhall River outflow. Of this, 0.20 [-0.01, +0.00] km^3 a^{-1} or 16 [-1, +0] % is sourced from glacier ice melt, 0.72 ± 0.01 km^3 a^{-1} or 56% is from snow melt, and 0.36 [-0.00, +0.02] km^3 a^{-1} or 28 [-0, +1] % is from rain. Figure 3.4 shows mean monthly volumes for each of these variables. Glacier runoff, which is not independent of these other hydrological variables but is composed of glacier ice melt, snow melt, and rain occurring over the glacier surface, comprises 0.58 km^3 a^{-1} or 45 [-1, +2] % of the total runoff quantity, while the remaining 55 [-2, +1] % is sourced from non-ice-covered terrain.

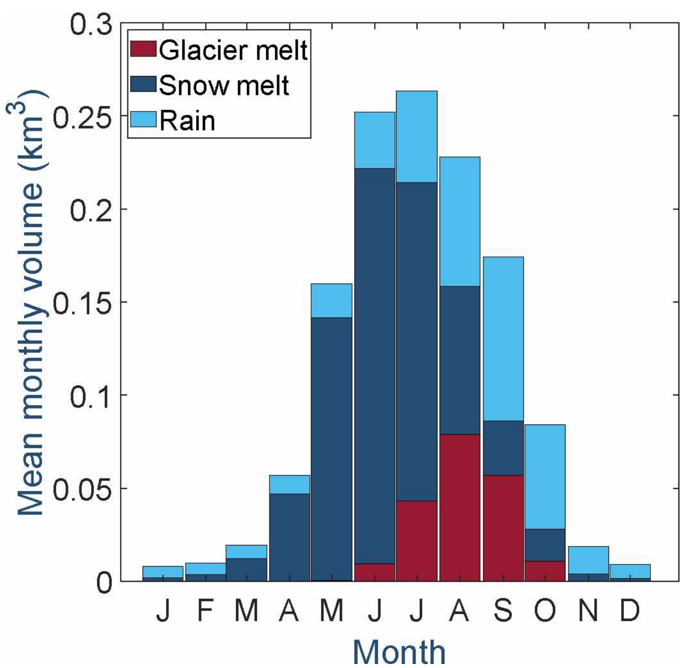

Figure 3.4: Mean 1980 to 2016 monthly total runoff for the full Mendenhall drainage to its outflow, partitioned by contributions from glacier ice melt, snow melt, and rain.

We examine all hydrological variables for trends in annual values over the 1980 to 2016 model period. Table 3.2 shows the results of all trend detection tests for annual sums, which are shown visually in Figure 3.5. Our results suggest an 8% increase in annual glacier runoff

Table 3.2: Results of trend detection tests for annual sums of modeled hydrological variables from 1980 to 2016 in the full Mendenhall drainage to its outflow. Columns show: 1) Hydrological variable; 2) Mean harmonized p-value; 3) Trend and units; 4) 95% confidence intervals, and; 5) Percent change from 1980 to 2016.

1) Variable	2) p-value	3) Trend (m w.e.^{3} a^{-1})	4) 95% confidence interval	5) % change
Total runoff	0.60	1.4e6	[-2.1e6, 6.7e6]	4.5
Glacier runoff	0.28	1.2e6	[9.4e4, 5.6e6]	8.0
Glacier ice melt	0.31	1.3e6	[7.9e4, 4.7e6]	24.3
Snow melt	0.76	-3.9e5	[-3.5e6, 1.3e6]	-1.8
Rain	0.55	1.5e6	[-3.9e5, 5.4e6]	15.2

volume since 1980 ($p = 0.28$). The test results also indicate a substantial increase of 24.3% in glacier ice melt contributions ($p = 0.31$). Although these p-values are somewhat high, the substantial effect sizes and all-positive 95% confidence intervals provide reasonable evidence that both of these variables have been increasing over the model period. Isolating these results to the portion of the Mendenhall drainage above the stream gauge increases our confidence further, as glacier ice melt shows an increase of 87% since 1980, with $p = 0.15$. Rain and snow melt trend detection tests over either spatial extent are less conclusive.

We also perform trend detection tests on monthly (May, June, July, August, and September) sums of hydrological variables over the 1980 to 2016 period. Of all variables tested, those which revealed the most statistically robust trends are August glacier runoff ($p = 0.02$), which has seen an increase of 15% over the study period, and August rain ($p \ll 0.001$) with an increase of 84%. Other variables for the months of May, June, and July show trends that are less statistically robust. Of all variables, glacier runoff is the only one that appears to be increasing in June ($p = 0.19$, +67%), July ($p = 0.18$, +14%), August ($p = 0.02$, +15%), and September ($p = 0.16$, +12%).

3.6.2 Stratified upper water column

In examining the oceanographic measurements at the Auke Bay CTD site, we observe a strongly stratified upper layer of the water column. Figure 3.6 shows measurements of salinity, density, and temperature for every month of August between 1997 to 2016, as well

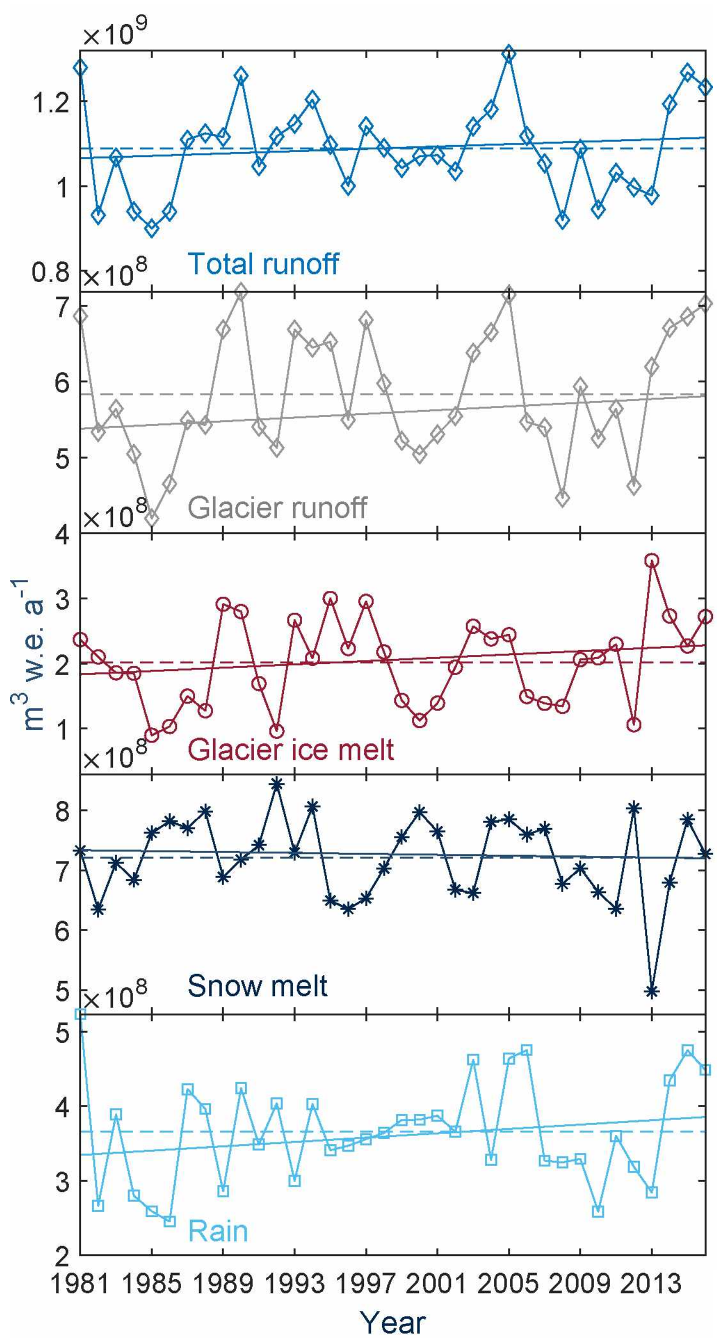

Figure 3.5: Time series, mean, and trends for the full Mendenhall drainage for different hydrological variables from 1980 to 2016. Time series are shown by markers, means by dashed lines, and trends by solid lines.

as the mean August profile for each variable. We select the month of August given the strongest glacier ice melt contributions seen in Figure 3.4). In the uppermost 10 m of the water column, we identify a layer of water that is substantially fresher (10 to 30 PSU) and less dense (1010 to 1023 kg m^{-3}) than standard sea water (~35 PSU and ~ 1025 kg m^{-3}). This is followed by a pronounced change in salinity and density at between 10 to 15 m depth, below which conditions more typical of unmodified sea water begin to dominate.

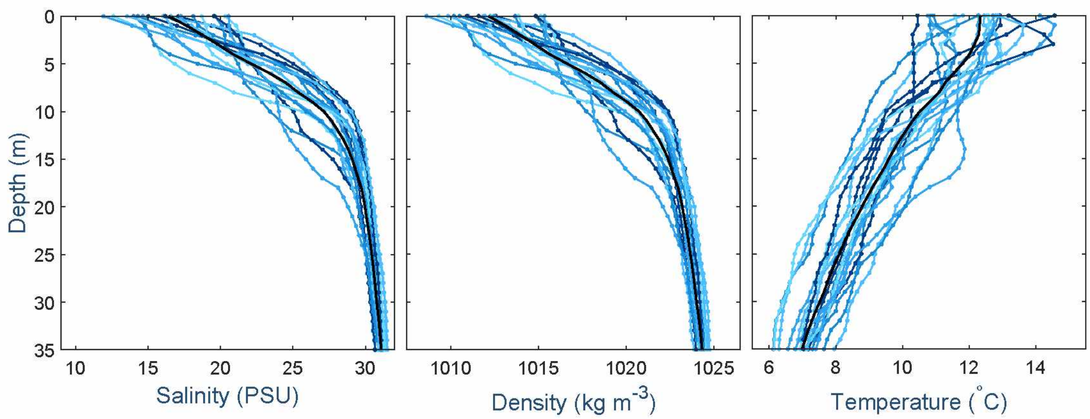

Figure 3.6: Individual and mean profiles of salinity, density, and temperature to depths of 35 m in the water column for all August measurement dates between 1997 to 2016. Individual years are shown in shades of blue (i.e. each blue line represents one August measurement), and the mean of all years appears in solid black.

We focus our analyses on salinity, as together with density it shows the clearest evidence for stratification in the water column (Figure 3.6), and because it is directly measured via conductivity, while density is derived from salinity and temperature together. Focusing on the upper 10 m of the water column, Figure 3.7 shows all salinity profiles for 1997 to 2016 as separated by the month in which they were collected. We observe that the strongest diversions from typical sea water salinity values in the upper water column occur in July and August, while May shows the least evidence of a stratified upper layer. This is the case despite high levels of freshwater runoff delivery to the coast in May, at the onset of peak snow melt season (Figure 3.4).

Figure 3.8 shows the time series of mean salinity for 1997 to 2016 for the top 5 m of the water column as separated by month, as well as mean values across time, and trends over time. Results of trend detection tests for all oceanographic variables are listed in Table 3.3). We find that while all months except July show decreasing trends in salinity, measurements in August reveal the largest and most robust trend ($p = 0.01$, with a change of -3.2 PSU since 1997), with June showing a change of equal size (-3.2 PSU) but less robust statistics (p = 0.23). Results are similar for density measurements, with a change of -0.7 kg m^{-3} in both August (p = 0.02) and June (p = 0.14).

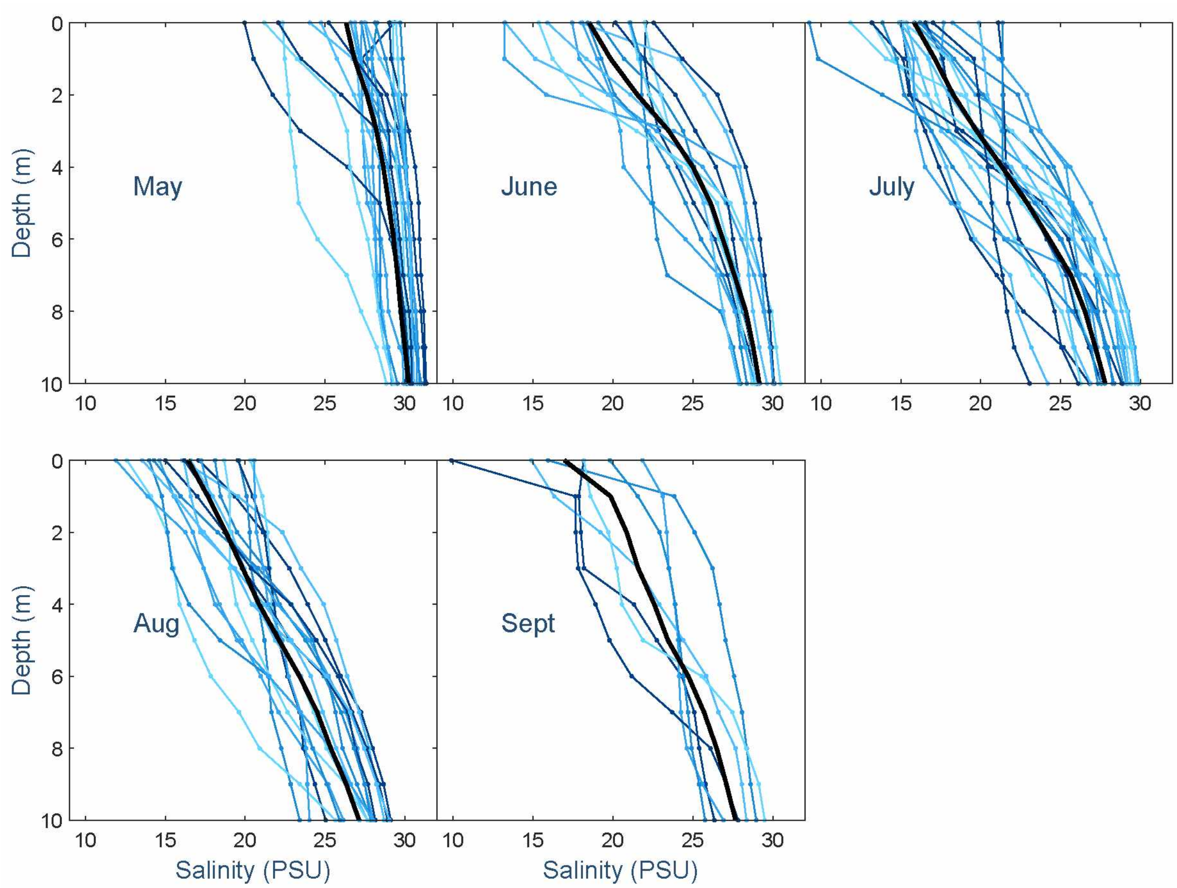

Figure 3.7: Monthly salinity profiles to 10 m depth in the water column, for years 1997 to 2016. Each individual year is shown in a shade of blue, and the mean of all years is shown in solid black.

3.6.3 Marine conditions linked to glacio-hydrological processes

Overall, the salinity and density analyses above serve as indications of a strong freshwater-modified upper layer of the water column, dominated by fresher and more buoyant water input. However, two puzzles remain. First, we aim to identify whether the freshwater input is glacially-sourced. Second, we seek to determine why temperatures behave inversely to what we would expect, with water column temperatures increasing towards the surface while

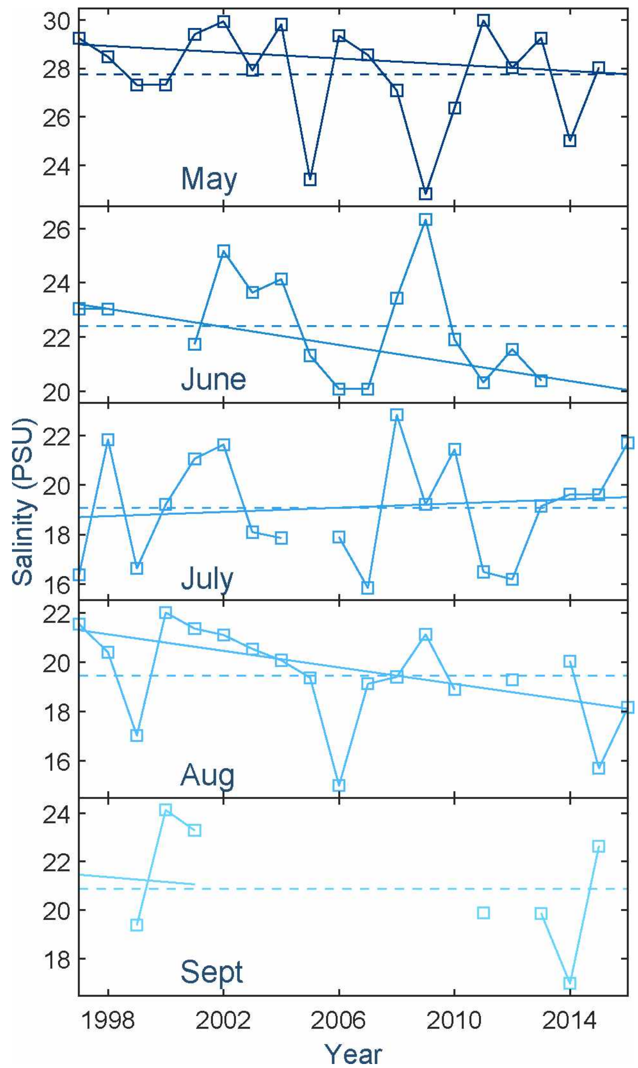

Figure 3.8: Time series, means, and trends in monthly salinity measurements from 1997 to 2016. Time series are shown by markers, means by dashed lines, and trends by solid lines.

density and salinity decrease. Results in Figure 3.9, which shows the correlation between all oceanographic variables (y axes) and modeled variables (x axes), answer both questions.

In the top row, Figure 3.9 shows that all oceanographic variables are strongly correlated with total runoff (density: $r^2 = 0.64$; temperature: $r^2 = 0.57$; salinity: $r^2 = 0.62$; all $p \ll 0.001$), though temperature still increases in the opposite direction. The second row repeats the same pattern, but shows even stronger correlations to glacier runoff (density: $r^2 = 0.68$; temperature: $r^2 = 0.70$; salinity: $r^2 = 0.66$; all $p \ll 0.001$). Glacier runoff also correlates to salinity more strongly than glacier ice melt in isolation ($r^2 = 0.09$, $p \ll 0.001$), snow

Table 3.3: Results of trend detection tests for mean salinity, density, and temperature measurements for the upper 5 m of the water column at the Auke Bay monitoring site. Columns show the month, along with p-values and absolute change from 1997 to 2016 for each salinity, density, and temperature.

1) Month	2) Salinity		3) Density		4) Temperature	
	p-value	change (PSU)	p-value	change (kg m^{-3})	p-value	change °C
May	0.48	-1.2	0.40	-0.4	0.23	1.1
June	0.23	-3.2	0.14	-0.7	0.92	0
July	0.62	0.8	0.73	0.2	0.26	0.7
August	0.01	-3.2	0.02	-0.7	0.06	1.8
September	0.55	-0.4	0.37	-0.9	0.07	3.2

melt ($r^2 = 0.03$, $p = 0.13$), rain ($r^2 = 0.33$, $p \ll 0.001$), or total precipitation ($r^2 = 0.19$, $p \ll 0.001$), none of which are shown graphically. These findings confirm that glacier runoff, which comprises rain, snow melt, and glacier ice melt generated at the glacier surface, exerts a stronger control over near-surface oceanographic conditions than any other hydrological variable, including total runoff, precipitation, or snow melt.

The third row of Figure 3.9 shows correlation between oceanographic measurements and air temperature, sampled at the Auke Bay monitoring site location. We find that this meteorological variable correlates strongly with water column temperature in particular ($r^2 = 0.73$) and more weakly with density and salinity ($r^2 = 0.48$ and $r^2 = 0.44$) (all $p \ll 0.001$). These findings suggest that while glacier runoff may be controlling both salinity and density of the upper portion of the water column, water temperature may still be dominated by atmospheric rather than hydrological conditions. However, in Figure 3.6, we see in the uppermost meters of the water column that some profiles show abrupt decreases of several degrees within the uppermost 2 to 5 m. We note also in Figure 3.9 that at the highest inputs of glacier runoff ($\geq \sim 50$ m^3 s^{-1}), water column temperatures appear to decrease. Together, these findings suggest that while air temperature exerts the dominant control, at very high air temperatures glacier runoff output is also high, such that these appear to have competing influence.

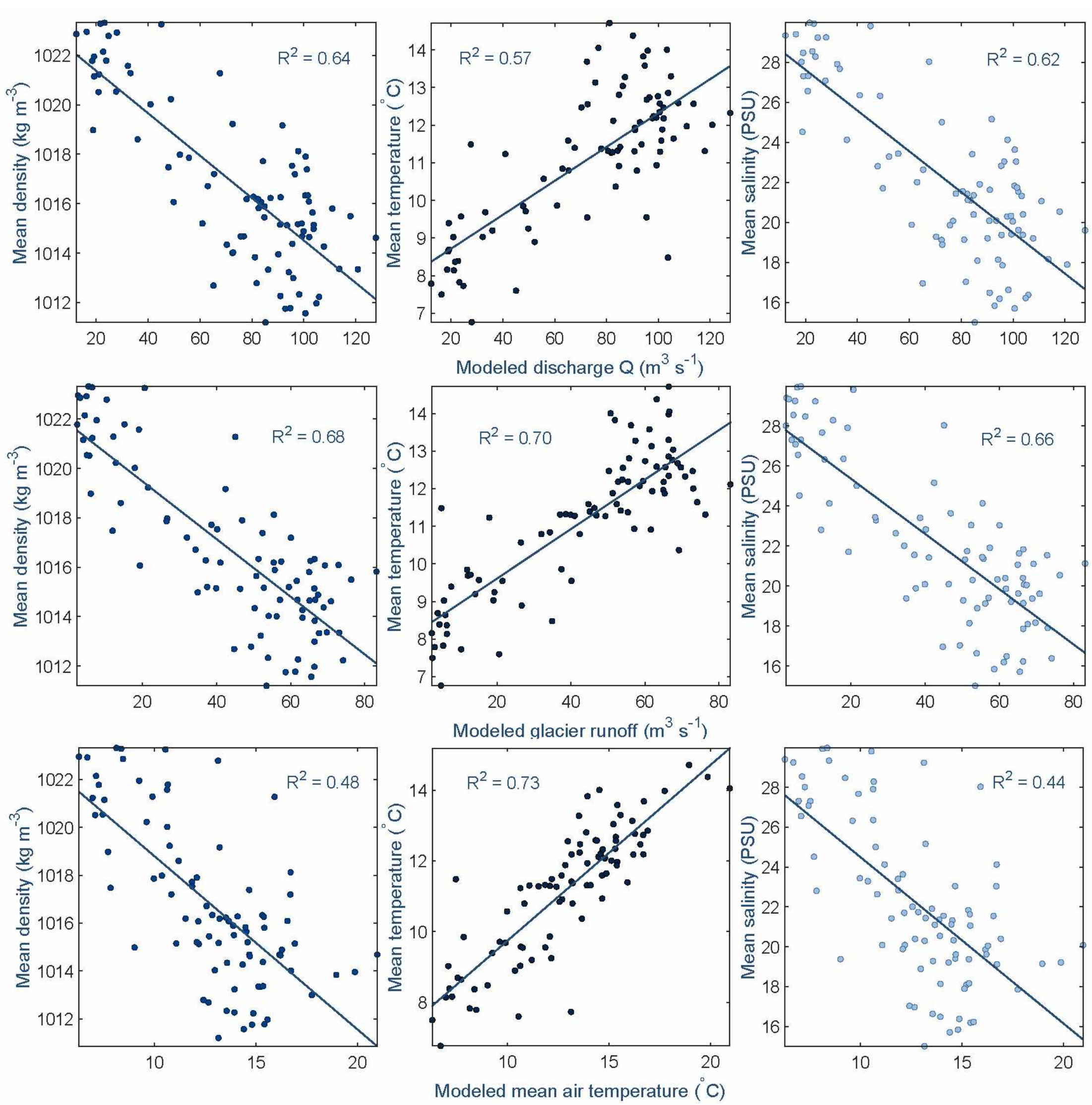

Figure 3.9: Scatter plots showing correlation between modeled freshwater discharge, glacier runoff, and air temperature from Mendenhall-Montana drainage versus density, water temperature, and salinity measurements from Auke Bay. Modeled freshwater discharge is shown in the top row, glacier runoff in the middle row, and air temperature in the bottom row versus Auke Bay measurements of density in the left column, water temperature in the middle column, and salinity in the right column. Each oceanographic data point represents the mean measurement for the top 5 m of the water column, as taken on a single date. Each hydrological variable is averaged over the seven days leading up to and including the exact CTD measurement date.

3.7 Discussion

Though our analyses focus on the Mendenhall drainage for terrestrial model output, and on Auke Bay for oceanographic measurements, we consider processes at both sites to be representative of broader regional patterns. As noted earlier, the Mendenhall Glacier exhibits a mass balance rate on par with the icefield mean (-0.73 $\pm$ 0.13 m w.e. a^{-1} vs -0.68 $\pm$ 0.15 m w.e. a^{-1}), suggesting its glacier runoff is reasonably representative of the icefield, which feeds the entire eastern shore of Lynn Canal. Although Auke Bay is within ~1 km of the mouth of the Mendenhall River, it is protected from direct outflow by a peninsula and several small islands, and is otherwise open to broader circulation. Our analyses reveal that oceanographic measurements correlate better with modeled discharge as we increase the length of the averaging window (14 days vs 1 day), suggesting there is a lag between freshwater delivery to the coast and arrival in Auke Bay. Lynn Canal as a whole also receives glacier freshwater input from dozens of creeks and large rivers along both its eastern and western shores, with shoreline distances between outlets rarely exceeding 10 km, a distance across which physical signatures in the water column due to glacial input are still measurable [*Arimitsu et al.*, 2016]. Taken together, this evidence suggests Auke Bay measurements may be more representative of regional conditions in Lynn Canal, rather than tied to specific outflow events from the Mendenhall River.

3.7.1 Water column structure controlled by glacier runoff

In this study, we confirm the presence of a glacially-modified upper layer of the water column in Auke Bay. Oceanographic measurements reveal a stratified zone of increasingly fresh and buoyant water from depths of ~10 to 15 m to the surface. Water column temperatures, however, generally increase towards the surface, as they are found to be strongly correlated with air temperature rather than controlled by glacier freshwater input. These results are supported by a study on oceanographic conditions in nearby Glacier Bay, a complex network of fjords 2 to 10 km in width with both tidewater glaciers and glacier river outflow. In the central bay, salinity decreased and water temperature increased from depth towards the surface, patterns the authors respectively attributed to freshwater input and air temperature [*Etherington et al.*, 2007].

Our findings indicate that of all the hydrological variables examined, glacier runoff, which includes rain, snow melt, and ice melt at the glacier surface, exerts the strongest control over nearshore oceanographic conditions. This is noteworthy considering that snow melt represents the dominant freshwater runoff component in the system at 56% of the mean annual runoff volume (Figure 3.4). However, it shows much weaker correlation ($r^2 = 0.03$, $p = 0.13$) than glacier runoff ($r^2 = 0.66$, $p \ll 0.001$, at 45% of total runoff). Our findings also indicate that precipitation is not the primary control ($r^2 = 0.19$, $p \ll 0.001$). While *Etherington et al.* [2007] were able to make some inferences about freshwater input into Glacier Bay from other physical parameters, the lack of observational data meant they could not identify which specific freshwater component might be the most important. Our study helps to fill this knowledge gap.

3.7.2 Comparison to other glacier fjord systems

Although it shares similarities, the water column structure we identify differs from some other Alaska glacier fjords. In the ~2 km wide Icy Bay in Alaska, within 1.5 km of the Yahtse Glacier terminus, water temperature generally decreases from 30 m depth to the surface [*Bartholomaus et al.*, 2013]. This is also true of measurements from the ~1 km wide LeConte Bay in Alaska, at a distance of 200 to 500 m from the LeConte Glacier calving face [*Motyka et al.*, 2003]. Moreover, our 10 to 15 m glacially-modified layer is shallower than the 30 m lens measured in Icy Bay, or the 35 to 40 m zone in LeConte Bay. In both cases, it can be assumed that glacially-modified water exerts a stronger control over water column temperature and the depth of the modified upper stratum, likely due to proximity to the glacier runoff input as well as a tidewater glacier terminus experiencing submarine melt, and due to topographical constraints in the narrow fjords.

Altogether, the glacially-modified oceanographic conditions we observe in Auke Bay are more similar to the broader central and lower portions of Glacier Bay [*Etherington et al.*, 2007] and the mouths of Icy Bay and College Fjord [*Arimitsu et al.*, 2016]. In these regions, salinity and water temperature display horizontal gradients with distance from the glacier runoff source, leading to glacially-modified layers that are ever present but less pronounced [*Arimitsu et al.*, 2016], and to areas where water temperature may be dominated by air temperature [*Etherington et al.*, 2007].

These differences highlight the extent to which local topography plays a strong role in shaping water column structure in different glacier fjord settings.

3.7.3 Implications

We identify in Auke Bay a 10 to 15 m layer of glacially-influenced water within the column, characterized by lower salinity and density. Though we do not have any measurements of turbidity in Auke Bay on which to rely, we can infer from the dominance of air temperature on water temperatures within the near-surface layer that solar radiation is able to penetrate to tens of meters. This inference of relatively low turbidity is also supported by observations of high phytoplankton concentrations in Auke Bay [*Ziemann et al.*, 1991], which depends on light availability [*Strom et al.*, 2016]. In fact, the depth stratum of 0 to 15 m has been identified as a zone of high primary production in Southeast Alaska estuaries; monitoring of spring phytoplankton blooms in Auke Bay by means of depth-integrated concentrations of chlorophyll *a* indicate that most phytoplankton occurs within the uppermost 15 m [*Ziemann et al.*, 1991]. Moreover, spring phytoplankton blooms constitute a substantial fraction of annual primary production in high-latitude seas and act as a crucial food source for higher trophic level organisms [*Strom et al.*, 2016].

Nutrient-rich pro-glacial marine environments have also been found to be occupied by a variety of marine consumers, such as copepods and euphausiids (crustaceans) and cold-water foraging fish [*Arimitsu et al.*, 2008; *Renner et al.*, 2012]. These populations in turn attract seabirds based on prey availability [*Arimitsu et al.*, 2016].

Through both our modeled hydrological variables and measured oceanographic conditions, we identify that substantial changes to these nearshore marine environments are already underway. Annual volumes of glacier runoff and glacier ice melt have increased since 1980 by 8% and 24.3%, respectively. The month of August in particular has shown a decrease in salinity values since 1997 of -3.2 PSU, in tandem with an increase in glacier runoff amounts by 15%. This increased proportion of glacial freshwater input is likely to continue inducing fresher and more buoyant near-surface oceanographic conditions, though consequences for water temperature may be more complex. Ultimately, we anticipate that ongoing glacier loss will induce ongoing changes in physical variables with depth and with distance from glacier runoff source, and will have varying interlinked influences on the function of nearshore coastal environments in the future.

3.8 Conclusions

This study leverages the coupled glacio-hydrological model SnowModel-HydroFlow to generate daily time series of freshwater variables between 1980 to 2016 for the Mendenhall Glacier drainage near Juneau, Southeast Alaska. Model simulations were calibrated to field, airborne, and satellite datasets, and validated against a regional mass change estimate from GRACE satellite gravimetry. We link terrestrial glacier discharge to oceanographic measurements in a nearshore marine environment, a connection not yet made through the use of high temporal resolution hydrological model results. We find that in May through September, salinity and density in the upper 10 to 15 m of the ocean water column display substantially reduced values relative to standard sea water (i.e. ∼10 to 30 PSU and 1010 to 1025 kg m^{-3}). We find that glacier runoff explains 66% of the variance in mean salinity in the uppermost 5 m ($p \ll 0.001$), and 68% in density ($p \ll 0.001$). Glacier runoff also correlates to salinity more strongly than either total runoff ($r^2 = 0.64$, $p \ll 0.001$), glacier ice melt ($r^2 = 0.09$, $p = 0.01$), snow melt ($r^2 = 0.03$, $p = 0.13$), rain ($r^2 = 0.33$, $p \ll 0.001$), or total precipitation ($r^2 = 0.19$ and $p \ll 0.001$). This indicates that freshwater that is sourced from or has been modified by glaciers exerts the dominant control over conditions in the upper water column in this area in Lynn Canal. However, strong positive correlations between water and air temperature ($r^2 = 0.70$, $p \ll 0.001$) indicate that water temperature in the upper column is more strongly influenced by air temperature than by glacier runoff. Nonetheless, on measurement dates associated with the highest glacier runoff inputs, water temperature in the uppermost 2 to 5 m decreases abruptly by several degrees Celsius, suggesting a dominant glacier runoff lens despite warm air temperature influences. Finally, we find decreasing trends from 1997 to 2016 in mean salinity of the upper 5 m of the water column in most months, with strongest decreases in August ($p = 0.01$, -3.2 PSU) that occur in tandem with an increase in August glacier runoff amounts ($p = 0.02$, 15%) between 1980 to 2016. Overall, this study reveals that glacier runoff exerts the strongest control over water column stratification within this nearshore environment, and that changes are underway within the uppermost depths, particularly in August. These findings have consequences for nearshore marine ecosystems, including for phytoplankton production, and for marine consumers such as crustaceans and cold-water pelagic forage fish that occupy this portion of the water column and favor glacially-influenced marine environments.

3.9 References

Amrhein, V., S. Greenland, and B. McShane (2019), Retire statistical significance, *Nature*, *567*.

Arendt, A., S. Luthcke, A. Gardner, S. O'Neel, D. Hill, G. Moholdt, and W. Abdalati (2013), Analysis of a GRACE global mascon solution for Gulf of Alaska glaciers, *Journal of Glaciology*, *59*(217), 913.

Arimitsu, M. L., J. F. Piatt, M. A. Litzow, A. A. Abookire, M. D. Romano, and M. D. Robards (2008), Distribution and spawning dynamics of capelin (mallotus villosus) in Glacier Bay, Alaska: A cold water refugium, *Fisheries Oceanography*, *17*(2), 137–146.

Arimitsu, M. L., J. F. Piatt, and F. Mueter (2016), Influence of glacier runoff on ecosystem structure in Gulf of Alaska fjords, *Marine Ecology Progress Series*, *560*, 19–40.

Bartholomaus, T. C., C. F. Larsen, and S. ONeel (2013), Does calving matter? Evidence for significant submarine melt, *Earth and Planetary Science Letters*, *380*, 21–30.

Beamer, J., D. Hill, A. Arendt, and G. Liston (2016), High-resolution modeling of coastal freshwater discharge and glacier mass balance in the Gulf of Alaska watershed, *Water Resources Research*.

Berthier, E., E. Schiefer, G. Clarke, B. Menounos, and F. Rémy (2010), Contribution of Alaskan glaciers to sea level rise derived from satellite imagery, *Nature Geoscience*, *3*, 92–95, doi:10.1038/NGEO737.

Berthier, E., C. Larsen, W. J. Durkin, M. J. Willis, and M. E. Pritchard (2018), Brief communication: Unabated wastage of the Juneau and Stikine icefields (southeast Alaska) in the early 21st century, *The Cryosphere*, *12*(4), 1523–1530.

Boyce, E. S., R. J. Motyka, and M. Truffer (2007), Flotation and retreat of a lake-calving terminus, Mendenhall Glacier, Southeast Alaska, USA, *Journal of Glaciology*, *53*(181), 211–224.

Crusius, J., A. W. Schroth, S. Gasso, C. M. Moy, R. C. Levy, and M. Gatica (2011), Glacial flour dust storms in the Gulf of Alaska: Hydrologic and meteorological controls and their importance as a source of bioavailable iron, *Geophysical Research Letters*, *38*(6).

Daly, C., M. Halbleib, J. I. Smith, W. P. Gibson, M. K. Doggett, G. H. Taylor, J. Curtis, and P. P. Pasteris (2008), Physiographically sensitive mapping of climatological temperature and precipitation across the conterminous United States, *International Journal of Climatology: A Journal of the Royal Meteorological Society*, *28*(15), 2031–2064.

Destouni, G., F. Hannerz, C. Prieto, J. Jarsjö, and Y. Shibuo (2008), Small unmonitored near-coastal catchment areas yielding large mass loading to the sea, *Global Biogeochemical Cycles*, *22*(4).

Elsberg, D. H., W. D. Harrison, K. A. Echelmeyer, and R. M. Krimmel (2001), Quantifying the effects of climate and surface change on glacier mass balance, *Journal of Glaciology*, *47*(159), 649–658.

Etherington, L. L., P. N. Hooge, E. R. Hooge, and D. F. Hill (2007), Oceanography of Glacier Bay, Alaska: Implications for biological patterns in a glacial fjord estuary, *Estuaries and Coasts*, *30*(6), 927–944.

Fellman, J. B., R. G. Spencer, P. J. Hernes, R. T. Edwards, D. V. D'Amore, and E. Hood (2010), The impact of glacier runoff on the biodegradability and biochemical composition of terrigenous dissolved organic matter in near-shore marine ecosystems, *Marine Chemistry*, *121*(1), 112–122.

Fellman, J. B., S. Nagorski, S. Pyare, A. W. Vermilyea, D. Scott, and E. Hood (2014), Stream temperature response to variable glacier coverage in coastal watersheds of Southeast Alaska, *Hydrological Processes*, *28*(4), 2062–2073.

Fellman, J. B., E. Hood, P. A. Raymond, J. Hudson, M. Bozeman, and M. Arimitsu (2015), Evidence for the assimilation of ancient glacier organic carbon in a proglacial stream food web, *Limnology and Oceanography*, *60*(4), 1118–1128.

Fergusson, E., J. T. Watson, A. Gray, and J. Murphy (2018), Annual survey of juvenile salmon, ecologically-related species, and biophysical factors in the marine waters of Southeastern Alaska, May–August 2016.

Fischer, G., S. Nachtergaele, H. Prieler, L. van Velthuizen, and D. Verelst (2008), Global Agro-Ecological Zones assessment for agriculture (GAEZ 2008), *IIASA, Laxenburg, Austria and FAO, Rome, Italy.*

Fountain, A. G., and W. V. Tangborn (1985), The effect of glaciers on streamflow variations, *Water Resources Research*, *21*(4), 579–586.

Gelaro, R., W. McCarty, M. J. Suárez, R. Todling, A. Molod, L. Takacs, C. A. Randles, A. Darmenov, M. G. Bosilovich, R. Reichle, et al. (2017), The Modern-Era Retrospective analysis for Research and Applications, version 2 (MERRA-2), *Journal of Climate*, *30*(14), 5419–5454.

Halsey, L. G. (2019), The reign of the p-value is over: What alternative analyses could we employ to fill the power vacuum?, *Biology Letters*, *15*(5), 20190,174.

Helsel, D. R., and R. M. Hirsch (2002), *Statistical methods in water resources*, vol. 323, US Geological Survey Reston, VA.

Hill, D., N. Bruhis, S. Calos, A. Arendt, and J. Beamer (2015), Spatial and temporal variability of freshwater discharge into the Gulf of Alaska, *Journal of Geophysical Research: Oceans*, *120*(2), 634–646.

Homer, C., J. Dewitz, L. Yang, S. Jin, P. Danielson, G. Xian, J. Coulston, N. Herold, J. Wickham, and K. Megown (2015), Completion of the 2011 National Land Cover Database for the conterminous United States – representing a decade of land cover change information, *Photogrammetric Engineering & Remote Sensing*, *81*(5), 345–354.

Hood, E., and L. Berner (2009), The effect of changing glacial coverage on the physical and biogeochemical properties of coastal streams in southeastern Alaska, *Journal of Geophysical Research*, *114*(13), G03,001, doi:10.1029/2009JG000971.

Hood, E., and D. Scott (2008), Riverine organic matter and nutrients in Southeast Alaska affected by glacial coverage, *Nature Geoscience*, *1*(9), 583–587.

Hood, E., J. Fellman, R. Spencer, P. Hernes, R. Edwards, D. D'Amore, and D. Scott (2009), Glaciers as a source of ancient and labile organic matter to the marine environment, *Nature*, *462*(7276), 1044–1048, doi:10.1038/nature08580.

Jansson, P., R. Hock, and T. Schneider (2003), The concept of glacier storage: A review, *Journal of Hydrology*, *282*(1-4), 116–129.

Kienholz, C., S. Herreid, J. Rich, A. Arendt, R. Hock, and E. Burgess (2015), Derivation and analysis of a complete modern-date glacier inventory for Alaska and northwest Canada, *Journal of Glaciology*, *61*(227), 403.

Komatsu, H. (2005), Forest categorization according to dry-canopy evaporation rates in the growing season: Comparison of the Priestley–Taylor coefficient values from various observation sites, *Hydrological Processes: An International Journal*, *19*(19), 3873–3896.

Larsen, C., R. Motyka, J. Freymuller, K. Echelmeyer, and E. Ivins (2005), Rapid viscoelastic uplift in Southeast Alaska caused by post-Little Ice Age glacial retreat, *Earth and Planetary Science Letters*, *237*, 548–560.

Larsen, C., R. Motyka, A. Arendt, K. Echelmeyer, and P. Geissler (2007), Glacier changes in southeast Alaska and northwest British Columbia and contribution to sea level rise, *Journal of Geophysical Research*, *112*(1), F01,007, doi:10.1029/2006JF000586.

Lenaerts, J., J. H. Angelen, M. R. Broeke, A. S. Gardner, B. Wouters, and E. Meijgaard (2013), Irreversible mass loss of Canadian Arctic Archipelago glaciers, *Geophysical Research Letters*, *40*(5), 870–874.

Lindsay, R., M. Wensnahan, A. Schweiger, and J. Zhang (2014), Evaluation of seven different atmospheric reanalysis products in the Arctic, *Journal of Climate*, *27*(7), 2588–2606.

Liston, G. E., and K. Elder (2006a), A distributed snow-evolution modeling system (SnowModel), *Journal of Hydrometeorology*, *7*(6), 1259–1276.

Liston, G. E., and K. Elder (2006b), A meteorological distribution system for high-resolution terrestrial modeling (MicroMet), *Journal of Hydrometeorology*, *7*(2), 217–234.

Liston, G. E., and C. A. Hiemstra (2008), A simple data assimilation system for complex snow distributions (SnowAssim), *Journal of Hydrometeorology*, *9*(5), 989–1004.

Liston, G. E., and S. H. Mernild (2012), Greenland freshwater runoff. Part I: A runoff routing model for glaciated and nonglaciated landscapes (HydroFlow), *Journal of Climate*, *25*(17), 5997–6014.

Loomis, B. D., and S. B. Luthcke (2014), Optimized signal denoising and adaptive estimation of seasonal timing and mass balance from simulated GRACE-like regional mass variations, *Advances in Adaptive Data Analysis*, *6*(01), 1450,003.

Luthcke, S., T. Sabaka, B. Loomis, A. Arendt, J. McCarthy, and J. Camp (2013), Antarctica, Greenland and Gulf of Alaska land-ice evolution from an iterated GRACE global mascon solution, *Journal of Glaciology*, *59*(216), 613–631, doi:10.3189/2013JoG12J147.

Lydersen, C., P. Assmy, S. Falk-Petersen, J. Kohler, K. M. Kovacs, M. Reigstad, H. Steen, H. Strøm, A. Sundfjord, Ø. Varpe, et al. (2014), The importance of tidewater glaciers for marine mammals and seabirds in Svalbard, Norway, *Journal of Marine Systems*, *129*, 452–471.

Martin, L., and F. E. Williams (1924), An ice-eroded fiord: The mode of origin of Lynn Canal, Alaska, *Geographical Review*, *14*(4), 576–596.

McGrath, D., L. Sass, S. O'Neel, A. Arendt, G. Wolken, A. Gusmeroli, C. Kienholz, and C. McNeil (2015), End-of-winter snow depth variability on glaciers in Alaska, *Journal of Geophysical Research: Earth Surface*, *120*(8), 1530–1550.

Melkonian, A. K., M. J. Willis, and M. E. Pritchard (2014), Satellite-derived volume loss rates and glacier speeds for the Juneau Icefield, Alaska, *Journal of Glaciology*, *60*(222), 743–760.

Motyka, R., L. Hunter, K. Echelmeyer, and C. Connor (2003), Submarine melting at the terminus of a temperate tidewater glacier, LeConte Glacier, Alaska, U.S.A., *Annals of Glaciology*, *36*(1), 57–65.

Nash, J. E., and J. V. Sutcliffe (1970), River flow forecasting through conceptual models part I: A discussion of principles, *Journal of Hydrology*, *10*(3), 282–290.

Neal, E., E. Hood, and K. Smikrud (2010), Contribution of glacier runoff to freshwater discharge into Gulf of Alaska, *Geophysical Research Letters*, *37*(6), L06,404, doi:10.1029/2010GL042385.

O'Neel, S., E. Hood, A. L. Bidlack, S. W. Fleming, M. L. Arimitsu, A. Arendt, E. Burgess, C. J. Sergeant, A. H. Beaudreau, K. Timm, et al. (2015), Icefield-to-ocean linkages across the northern Pacific coastal temperate rainforest ecosystem, *BioScience*, *65*(5), 499–512.

O'Neel, S., D. McGrath, G. Wolken, E. Whorton, S. Candela, L. Sass, C. McNeil, E. Baker, E. Peitzsch, D. Fagre, A. Clark, C. Florentine, Z. Miller, J. Christian, K. Christianson, E. Babcock, M. Loso, A. Arendt, E. Burgess, and A. Gusmeroli (2018), Ground penetrating radar data on North American glaciers, version 2.1, U.S. Geological Survey data release, doi:10.5066/F7M043G7.

Pelto, M., J. Kavanaugh, and C. McNeil (2013), Juneau Icefield mass balance program 1946–2011, *Earth System Science Data*, *5*(2), 319–330.

Pfeffer, W. T., A. A. Arendt, A. Bliss, T. Bolch, J. G. Cogley, A. S. Gardner, J.-O. Hagen, R. Hock, G. Kaser, C. Kienholz, et al. (2014), The Randolph Glacier Inventory: A globally complete inventory of glaciers, *Journal of Glaciology*, *60*(221), 537–552.

Priestley, C., R. Taylor, et al. (1972), On the assessment of surface heat flux and evaporation using large-scale parameters, *Monthly Weather Review*, *100*(2), 81–92.

Ramage, J. M., B. L. Isacks, and M. M. Miller (2000), Radar glacier zones in Southeast Alaska, USA: Field and satellite observations, *Journal of Glaciology*, *46*(153), 287–296.

Reichle, R. H., C. S. Draper, Q. Liu, M. Girotto, S. P. Mahanama, R. D. Koster, and G. J. De Lannoy (2017), Assessment of MERRA-2 land surface hydrology estimates, *Journal of Climate*, *30*(8), 2937–2960.

Renner, M., M. L. Arimitsu, and J. F. Piatt (2012), Structure of marine predator and prey communities along environmental gradients in a glaciated fjord, *Canadian Journal of Fisheries and Aquatic Sciences*, *69*(12), 2029–2045.

Roth, A., R. Hock, T. V. Schuler, P. A. Bieniek, M. Pelto, and A. Aschwanden (2018), Modeling winter precipitation over the Juneau Icefield, Alaska, using a linear model of orographic precipitation, *Frontiers in Earth Science*, *6*, 20.

Royer, T. (1981), Baroclinic transport in the Gulf of Alaska. Part II. A fresh water driven coastal current, *Journal of Marine Research*, *39*, 251–266.

Shulski, M., and G. Wendler (2007), *The Climate of Alaska*, 216 pp., University of Alaska Press.

Stabeno, P., N. Bond, A. Hermann, N. Kachel, C. Mordy, and J. Overland (2004), Meteorology and oceanography of the northern Gulf of Alaska, *Continental Shelf Research*, *24*(7-8), 859–897.

Strom, S. L., K. A. Fredrickson, and K. J. Bright (2016), Spring phytoplankton in the eastern coastal Gulf of Alaska: Photosynthesis and production during high and low bloom years, *Deep Sea Research Part II: Topical Studies in Oceanography*, *132*, 107–121.

Wilson, D. J. (2019), The harmonic mean p-value for combining dependent tests, *Proceedings of the National Academy of Sciences*, *116*(4), 1195–1200.

Wouters, B., J. Bonin, D. Chambers, R. Riva, I. Sasgen, and J. Wahr (2014), GRACE, time-varying gravity, Earth system dynamics and climate change, *Reports on Progress in Physics*, *77*(11), 116,801.

Wrzesien, M. L., M. T. Durand, and T. M. Pavelsky (2019), A reassessment of North American river basin cool-season precipitation: Developments from a new mountain climatology dataset, *Water Resources Research*, doi:10.1029/2018WR024106.

Young, J. C. (2019), Gilkey Glacier mass balance point observations 2013-2015, Southeast Alaska, HydroShare, doi:10.4211/hs.275f3521cc834467a34c051a716a3b30.

Young, J. C., A. Arendt, R. Hock, and E. Pettit (2018), The challenge of monitoring glaciers with extreme altitudinal range: Mass-balance reconstruction for Kahiltna Glacier, Alaska, *Journal of Glaciology*, doi:10.1017/jog.2017.80.

Young, J. C., E. Pettit, A. Arendt, E. Hood, G. Liston, and J. Beamer (2020 – in review), A changing hydrological regime: Trends in magnitude and timing of glacier ice melt and glacier runoff in a high latitude coastal watershed, *Water Resources Research*.

Ziemann, D., L. Conquest, M. Olaizola, and P. Bienfang (1991), Interannual variability in the spring phytoplankton bloom in Auke Bay, Alaska, *Marine Biology*, *109*(2), 321–334.

Ziemen, F. A., R. Hock, A. Aschwanden, C. Khroulev, C. Kienholz, A. Melkonian, and J. Zhang (2016), Modeling the evolution of the Juneau Icefield between 1971 and 2100 using the Parallel Ice Sheet Model (PISM), *Journal of Glaciology*, *62*(231), 199–214.

Chapter 4: "You really see it": Environmental identity development through interacting with a climate change-impacted glacier landscape[3]

4.1 Abstract

The global climate crisis continues to endanger the well-being of natural environments and the people who depend on them. However, school science for youth may not always directly or completely address climate change. In this context, outdoor education programming may offer an opportunity to better connect youth to the changes underway, by exposure to landscapes that are directly impacted. To date, little work has explored how experiencing first-hand a climate change-impacted landscape may support environmental identity shifts. This study explores these ideas in the context of a wilderness science program for youth in a glacier-dominated landscape (*Girls on Ice*). We use a qualitative approach to investigate how participants experience environmental identity development through interacting with the glacier landscape and learning about climate impacts, relying on Clayton's (2003) environmental identity model as a theoretical construct. We find that two aspects of environmental identity shifted the most: (1) relatedness to the natural environment, and (2) pro-environmental motivation. Emergent themes from the analysis reveal that those gains arise from better understanding how ecosystems are interconnected, understanding human impacts on the environment, and witnessing first-hand the scale and rate of glacier loss. We discuss the implications for outdoor educators to consider leveraging glaciers in future climate change education initiatives, given that they offer imposing visual evidence of the cumulative impacts since the onset of anthropogenic climate change. Ultimately, our findings highlight that personally witnessing a climate-impacted landscape may be powerful in promoting better stewardship in response to the climate crisis.

[3]Young, J.C., Carsten Conner, L., and E. Pettit (2020). *"You really see it": Environmental identity development through interacting with a climate change-impacted glacier landscape.* Manuscript in preparation.

4.2 Introduction

As the global climate continues to warm, consequences for landscapes, ecosystems, and people continue to expand and intensify. From increasing heat waves to melting sea ice and glaciers, impacts from ongoing climate warming are numerous, threatening, and increasing [*Masson-Delmotte et al.*, 2018]. While many youth across the globe today play active and leading roles in the movement to combat climate change [*Fisher*, 2016], others remain skeptical and dismissive of the seriousness of the issue [*Ojala*, 2015]. Moreover, while some school environmental science curricula have played an important role in overcoming skepticism through climate literacy [*Stevenson et al.*, 2014], in other instances school science may not directly or completely address climate change [*Meehan et al.*, 2018; *Choi et al.*, 2010]. In order to continue growing youth engagement in climate change issues, outdoor environmental education programs (hereafter 'outdoor education' for brevity) may be primed to help fill the gap.

Outdoor education offers opportunities to learn in, about, and for the outdoors [*Ford et al.*, 1986], combining the tenets of experiential and environmental education [*Adkins and Simmons*, 2002]. Experiential education centers on direct experience and in-context action, infused with critical reflection aimed at increasing knowledge and skills and clarifying values [*Ford et al.*, 1986; *Kolb*, 2014]. Environmental education focuses on showcasing how natural environments function and how humans can act sustainably [*Stapp*, 1969]. It carries as principal goals the preservation of a healthy, diverse ecosystem for future generations, and an engaged citizenry motivated to act on behalf of that goal [*Tanner*, 1980]. Taken together, these tenets provide a powerful platform for providing participants in outdoor education programming an opportunity to be not only immersed in nature, but also moved towards action by it. One way in which outdoor education can be shaped to help encourage pro-environmental behavior is through promoting identity shifts among people who experience nature [*McGuire*, 2015]. Environmental identity is the aspect of identity that encompasses one's relationship to nature and involves the ways in which people position themselves and are positioned with respect to the non-human natural world. It is both a product based on personal history, connection, and/or social influences, as well as a force that compels certain types of behavior toward the environment [*Clayton*, 2003]. Because of this motivational potential, providing opportunities for people to experience first-hand a climate change-impacted landscape may help to shift stances towards the natural world through a personal encounter with an environment in flux. However, while many studies to date have explored the links between outdoor education and environmental identity development (e.g. *Williams and Chawla* [2016]; *McGuire* [2015], few have done so in the context of climate change.

Outdoor education opportunities in glacier landscapes offer an ideal opportunity to bear witness to change. In much of the world including Alaska and Washington, glaciers began to retreat concurrently with the late 19th-century onset of the Industrial Revolution [*Crutzen and Stoermer*, 2000]. Shrinking mountain glaciers are directly linked to climate change, with changes in size that correlate strongly with global air temperatures [*Dyurgerov and Meier*, 2000]. Today, the centennial-scale retreat of glaciers represents the cumulative effects of climate change [*Roe et al.*, 2017], thereby serving as visual evidence of climate change in places where that difference in size can be seen on the landscape. For these reasons, glaciers have in recent decades become a prominent symbol of climate change in popular media [*Doyle*, 2009; *Carey*, 2007], largely attributable to glaciers' dual connection to climate change both as archives of past climate that can be retrieved in ice cores and as victims of rapid disintegration in current-day warming [*Carey*, 2007]. It is perhaps no surprise that melting glaciers and sea ice have become the single most popular response when members of the U.S. public are asked, "What is the first thought or image that comes to your mind when you think of global warming?" [*Leiserowitz*, 2005].

To date, little work has explored the potential for interactions with glaciers to support pro-environmental outcomes in the context of climate change by shifting aspects of environmental identity. This study examines how a residential youth mountaineering and science expedition, *Girls on Ice*, may develop participants' environmental identity through a week of living on, exploring, and scientifically studying the rapidly and visibly changing landscapes surrounding two Pacific Northwest glaciers.

4.3 Theoretical perspective

4.3.1 Environmental identity

Environmental identity encompasses reflection on the natural, non-human environment and, in particular, on one's position within it. We situate our study in Clayton's (2003) conceptual and operational definition for environmental identity, which is rooted in work by *Rosenberg* [1981] that discusses the ways in which aspects of self-concept/identity are both a product and a force. Clayton proposes that environmental identity is: "one part of the way in which people form their self-concept: a sense of connection to some part of the nonhuman natural environment... that affects the ways in which we perceive and act toward the world [*Clayton*, 2003, p.46]. Clayton also adds that environmental identity is a collective identity, whereby one may feel a sense of connection not only to the natural world but also to others with similar views. Indeed, identification with a group who possess similar worldviews and/or political affiliations can significantly influence one's environmental attitudes and behaviors, prompting group members to act in more or less pro-environmental ways [*Fielding and Hornsey*, 2016].

In Clayton's formulation, along with social influences, many other factors intersect to dictate how one feels about the natural environment, where/how one feels they fit into it, and how one behaves towards it. Clayton proposes that environmental identity is influenced by such elements as: personal history, emotional attachment, autonomy, relatedness, competence, and pro-environmental motivation. We briefly summarize Clayton's description of each element here.

Personal history refers to one's prior experiences in nature which, whether positive or negative, impact the way in which one thinks about and behaves towards the natural environment. Related to this, emotional attachment is based on experiences that are emotionally significant and that stem from a tendency for humans to be drawn to natural landscapes. Autonomy then describes how in those natural landscapes one may feel a sense of freedom from the expected behaviors and constraints of other social settings, a scenario which can offer a chance to build self-actualization by feeling at ease to be oneself.

Relatedness to the natural environment occurs when one has the "opportunity to feel like a part of a functioning system" [*Clayton*, 2003, p.50]. While for some, this may be experienced in a spiritual sense, for others it may arise from feeling part of a larger ecosystem, environment, or world. *Naess* [1973] was the first to coin the term 'deep ecology' to refer to a movement that rejects anthropomorphism and profit-driven motivations ('shallow ecology') in favor of maintaining biological diversity, egalitarianism with other forms of life, and relational links between ecosystem components, all driven by ecological equilibrium first and foremost. This concept encourages thinking of one's self as a part of, and not separate from, the natural world.

Competence in a natural setting is rooted in a sense of self-sufficiency, an ability to travel around independently, and the capacity to survive and thrive in the outdoors while facing any fears. Increased competence leads to environmental identity development because the natural environment serves well as a setting against which to test oneself, and to learn one's limits and abilities. *Hinds* [2011] observed for example that a residential woodland adventure program for marginalized adolescents resulted in improved self-identified perceptions of skills-based competence. The human inclination for competence is also cited as a common driver in pro-environmental motivation [*De Young*, 2000].

Pro-environmental motivation is the element of environmental identity that acts as a force, by enabling one to see how they are personally relevant in environmental issues, thereby affecting their thinking and behavior [*Clayton*, 2003]. Many studies have identified different experiences that can encourage this type of mindset. Such benefits as time outdoors in pristine environments [*Cachelin et al.*, 2009], personal growth and transformation [*D'Amato and Krasny*, 2011], and even strong autobiographical memories many years after the experience [*Liddicoat and Krasny*, 2014] were all identified as not only the most significant outcomes of different outdoor education programs, but also as the most strongly linked to pro-environmental behavior. Another significant body of research has connected pro-environmental behavior to having significant life experiences outdoors [*Chawla*, 2006]. *Tanner* [1980] was the first to document that for many who chose a career in conservation, memorable youthful experiences in nature, and particularly in environments relatively untouched by humans, were cited as the most significant experiences in developing their pro-environmental interests. Decades later, another study that conducted interviews with youth environmental leaders again confirmed that formative life experiences in the outdoors were still described as key to the subjects' interests in pro-environmental activism [*Arnold et al.*, 2009].

In this study, we draw from Clayton's theory on environmental identity development to help us answer: in what ways does interacting with a climate change-impacted glacier landscape influence aspects of participants' environmental identity?

4.4 Context of the study

This study was undertaken in the context of the *Girls on Ice* program, a science, art, and mountaineering experience for female-identifying youth aged 16 to 18. Each year, two teams of nine participants and three to four instructors spend twelve days together including eight days on a mountaineering expedition in a wilderness setting dominated by glaciers. *Girls on Ice* was developed by author Pettit in Washington State in 1999 and has since been adapted for a number of other locations, including Alaska. The Washington program takes place on Mount Baker's Easton Glacier, and the Alaska program is located on the Gulkana Glacier in the Eastern Alaska Range. During the field portion of the program, participants live on, explore, and study a glacier and its surrounding landscape (Figure 4.1), through instructor-led and participant-designed scientific field studies (Figure 4.2), mountaineering objectives (Figure 4.3), and art activities. The program emphasizes the interconnected nature of different disciplines (e.g. art, mountaineering, and physical, chemical, and biological sciences).

The *Girls on Ice* program aims to provide the opportunity to participants of diverse cultural, ethnic, socio-economic, and geographic backgrounds from across the United States (with occasional international participants). In order to remove barriers to access, the expedition is provided at no cost to the participant, although a small, individualized fundraising goal is encouraged to instill a sense of commitment.

Each program invites applications from female-identifying youth. Several studies have examined the benefits of outdoor education programming for all female-identifying participants, such as promoting feelings of safety, increased connection to others, and freedom from stereotypes [*Whittington et al.*, 2011], as well as long-term resiliency [*Whittington et al.*, 2016]. Moreover, such programs have been found to help in overcoming barriers to female participation in the outdoors such as access, peer and family expectations, and physical and environmental factors [*Culp*, 1998]. The *Girls on Ice* program participates in this educational model through an all-female-identifying team of instructors, coordinators and volunteers, as well as participants. Nonetheless, this study is not rooted within a feminist theoretical framework, in the sense that it does not focus on the female lived experience and the nature of gender inequality. Rather, this study is framed to examine environmental identity rather than gender identity, particularly as it relates to participants' experience of and reaction to a wilderness environment in flux.

Another thorough description of *Girls on Ice* can be found in *Carsten Conner et al.* [2018], a study that focused on the impacts of the program on the participants' notions about the practice of field science. Here, we outline the program elements of greatest relevance to environmental identity development.

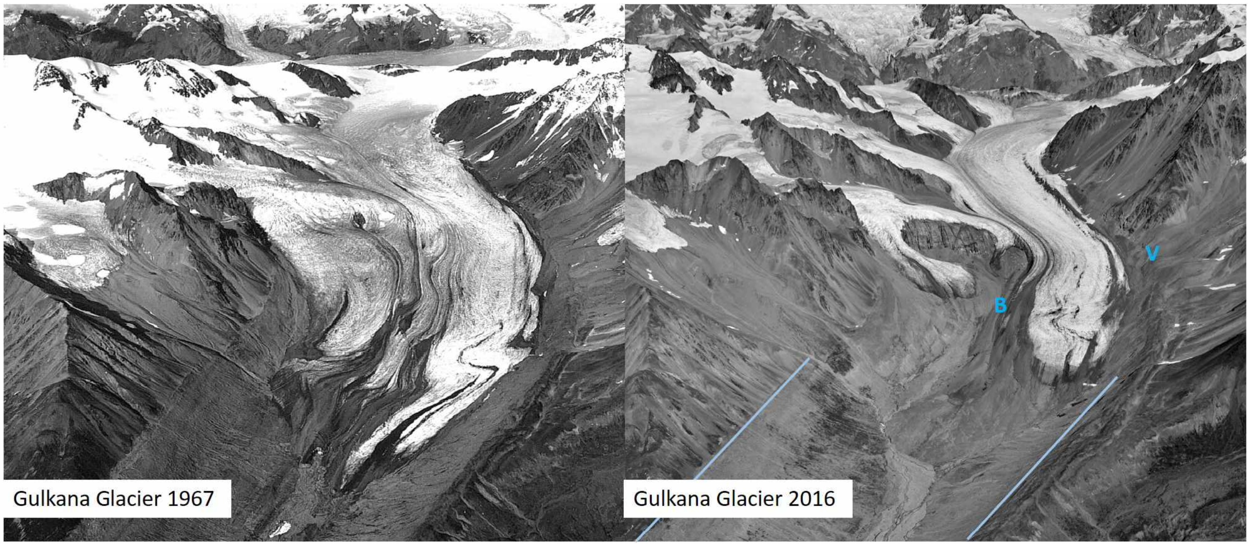

Figure 4.1: Aerial view of Gulkana Glacier, site of the *Girls on Ice Alaska* program, in 1967 and 2016. Left and right photos respectively indicate the extent of the glacier in 1967 and 2016, showing dramatic retreat and thinning over the past 50+ years. Features of interest are highlighted in the right panel, including: the main campsite for the 8-day backcountry portion of the trip (marked as 'B' – for a close-up view, see Figure 4.4); one of our hiking objectives (V), a viewpoint atop the late 1800s (i.e. Little Ice Age) lateral moraine, approximately 250 m above the current-day ice surface (Figure 4.6); c) the late 1800s areal extent of the glacier (light blue lines), delineating the bare, more recently exposed light grey slopes beneath the more weathered rock above. Modified from repeat photos courtesy of the United States Geological Survey (https://www.usgs.gov/news/fifty-years-glacier-change-research-alaska). Landscape features on and around the Easton Glacier on Mount Baker are very similar.

4.4.1 Camping on, living near, and exploring a glacier

During the eight days in the field, participants in *Girls on Ice* are completely immersed in a glacier-dominated alpine landscape (Figure 4.1). Participants camp in tents pitched directly beside the glacier, in Washington, or on top of it on a band of rocks, in Alaska (Figure 4.4). Daily excursions allow for exploration of different glacier zones, such as crevasse fields (Figure 4.5), zones with meltwater features, recently deglaciated areas, and moraines (rubble piles marking the former glacier extent on the hillside). During each program, participants also stand beneath and climb 100 meters to the top of the lateral moraine, a feature analogous to a 'high water mark' left behind as each glacier has thinned in the past ~150 years (Figure 4.6). Similarly, the terminal moraine, a hill of rubble marking the glacier tongue's former

Figure 4.2: Participants measure glacier meltwater volume at a stream on the Gulkana Glacier, as part of their participant-led field experiment on meltwater input into the river downstream. Photo by Joanna Young.

position, provides a visual sense of scale to the ~2.5 - 3 km of retreat experienced by each glacier.

4.4.2 Modeling pro-environmental behavior

The *Girls on Ice* program teaches and models a 'leave no trace' ethic, a standard in the outdoors industry that espouses minimizing one's environmental footprint when traveling through and camping in nature. Instructors teach leave no trace principles on the first day of the program, and revisit them routinely throughout the days in the field, both through explicit discussion and through modeled behavior. Principles of leave no trace include camp-

Figure 4.3: Ascending on rope teams to the summit of a local peak during *Girls on Ice Alaska*. Photo by Joanna Young.

ing on durable surfaces devoid of delicate plant life, and picking up and disposing of even the smallest spilled food scraps or other 'micro-trash.'

4.4.3 Learning ecosystem interconnectedness

As part of its teaching philosophy, *Girls on Ice* aspires to showcase the interconnectedness of landscapes, ecosystems, and humans. Science instructors carry expertise in a range of fields, including glaciology, geology, wildlife biology, and oceanography. Much instruction is devoted to demonstrating how these fields connect. For example, instructors guide the participants to mentally trace the path of glacial meltwater from source to sea, along the way discussing its influences on ecosystem components as broad as salmon fisheries and

Figure 4.4: Participants gather for a meal at the kitchen area at base camp on the Gulkana Glacier in Alaska, in front of the active Gabriel Icefall. Participants' sleeping tents are also in the vicinity, located atop the same exposed band of glacier-eroded cobbles. Photo by Joanna Young.

ocean acidity. Instructors also link these lessons back to humans, by discussing both human impact on ecosystems through resource use and climate modification and, simultaneously, the dependence of humans on the health of those same oceans, fisheries, and wildlife populations.

4.5 Methodology

This study is a bounded case study [*Bogdan and Biklen*, 2007] that investigates the experience of fifteen girls learning and camping in a glacierized environment during the *Girls on Ice* program. We use a qualitative methodology, an approach aimed at "understanding how people interpret their experiences, how they construct their worlds, and what meaning

Figure 4.5: Exploring a glacier crevasse as part of a daily excursion from base camp on Gulkana Glacier, Alaska. Photo by Joanna Young.

they attribute to their experiences" [*Merriam and Tisdell*, 2015]. A qualitative methodology for data collection and analysis is well-suited to our study, as we aim to better understand how participants interpret their experience of the glacier landscape, how that may influence how they construct their post-program worlds in terms of pro-environmental behavior, and what meaning they attribute to their time on a glacier during the *Girls on Ice* program. Moreover, our interest is in understanding the mechanisms behind any changes in elements of participants' environmental identity in the context of *Girls on Ice*, a task better suited to descriptive qualitative data than to quantitative metrics.

We use a participant-observer approach, in which the lead author worked alongside the participants and collected data. This gave her an "insider's view" and helped reduce any

Figure 4.6: View from atop the lateral moraine of Gulkana Glacier, Alaska. The glacier is seen in white in the photo's center-right. The lateral moraine is a feature analogous to a 'high water mark' left behind as the Gulkana Glacier has thinned and retreated since the most recent glacial maximum. The extent of the glacier approximately 150 years ago can be seen as the skyline ridge beginning at the left of the photo and continuing as a ring of lighter grey (more recently exposed) rocks against the mountains all the way to the right of the photo (identified by arrows on both sides). The modern glacier meltwater river intersects the valley in the middle. This ring indicates a loss of glacier ice of ∼100 m in height and ∼3 km in length since the late 1800s. Photo by Joanna Young.

potential reactivity on the part of participants. The other authors were involved with data analysis, program design, and/or writing.

4.5.1 Participants

Girls on Ice participants are recruited and selected through an online application process that asks short essay questions to learn about each applicant's life interests, day-to-day life, and motivation for applying. The participants who are selected represent a diversity of geographies, ethnicity, socio-economic backgrounds, family situations, personalities, interests, academic background, and outdoor and science experience, with preference for applicants who would not otherwise have such an opportunity. We offered enrollment in this study to the 18 applicants selected for one year of programming in the mid-2010s (nine for each of two *Girls on Ice* expeditions). Of these, one declined to participate, and two did not attend the program due to unforeseen circumstances. In total, our sample size was 15 (7 and 8 on each of the Alaska and Washington programs, respectively). Participants ranged from 16 to 18 years old.

4.5.2 Interviews

One-on-one interviews were conducted during the last two days of each program at the learning institutes (i.e. after the field expedition). These interviews were conducted either in person (Alaska program) or remotely over video-conference (Washington program). The interviewer was a person external to this study but familiar with the *Girls on Ice* program, who was not previously acquainted with the participants. The interview protocol included seven multi-part questions designed to target the participants' ideas, stances, and feelings about environment, ecosystems, and climate change as a result of having spent time in the wilderness and, specifically, on a glacier. Some questions were formatted as retrospective, asking each individual to think back to the beginning of the program and to compare to their thoughts at the end. The interviews were semi-structured, allowing for the interviewer to follow up on particular statements, ask for or provide clarification, or reorder questions when appropriate [*Rubin and Rubin*, 2011]. Some examples of multi-part questions include: "Describe how you feel about the environment and ecosystem. Has *Girls on Ice* changed how you feel about the environment and ecosystem, and if so, how? How did you feel about the environment before participating in *Girls on Ice*?" and "What was it like to be on a glacier? Did living on, exploring and learning about a glacier impact how you feel about the environment and/or climate change? If so, how?" All interviews were audio-recorded and then transcribed. Interviews ranged between 10 to 20 minutes in length.

4.5.3 Qualitative survey responses

Survey data was also collected from participants both during the week after the program (n=15), and approximately one year after the program (n=11), using the online platform SurveyMonkey. In these, participants were asked eight open-ended (no character limit) text box questions. Some questions were designed to learn generally about participants' experience during the program (e.g. "What did you learn about yourself on *Girls on Ice*?"), while others were more targeted towards understanding participants' experiences of the glacier (e.g. "Did exploring a glacier landscape change how you understand the environment and/or climate change? Why or why not?"). Some questions were again phrased as retrospective, in order to capture change resulting from the *Girls on Ice* program.

4.5.4 Data analysis

To discover patterns within the interview data, we employed a directed qualitative content analysis approach [*Hsieh and Shannon*, 2005], whereby codes were initially developed from theory, then refined as described below. Two authors (Young and Carsten Conner) first developed a coding scheme using select elements of the environmental identity framework in *Clayton* [2003] that were relevant to independent memos taken during a preliminary reading of four sample transcripts. After an initial round of coding on those same four transcripts followed by extensive discussion, the coding scheme was further refined by collapsing select overlapping codes, eliminating others due to a relative scarcity of excerpts, and adding additional codes that were not present in Clayton's framework but that were relevant to our research question and present throughout the data. At this stage, inter-rater reliability was calculated as pooled Kappa (k = 0.87; [*De Vries et al.*, 2008]). Author Young then performed the final round of coding of all interview transcripts using Dedoose software. We included several child codes grouped under parent code headings. Code descriptions and examples are provided in Table 4.1.

Table 4.1: Final codes applied to interview excerpts, along with descriptions and examples of each.

Code	Definition	Example
Pro-environmental behavioral motivation/ intentions	Participant speaks about a desire to act in a way that is environmentally responsible	"It makes me want to learn more about the environment and spread awareness." "I definitely want to do what I can to protect [the environment] and preserve it."
Emotional connection to landscape	Language describing an emotional connection to the landscape encountered in *Girls on Ice*	"You just really start to appreciate the place because of all the memories that you formed there. And so it seems devastating that it would ever not be the same."
Feelings about or experiences with the environment/nature	Descriptions of feelings about or experiences with the environment/outdoors/nature, the landscape, or the glacier	"Being out on the glacier, and not only getting to learn about it, but also getting to see and touch it, that was pretty awesome." "I felt powerful, too, because I was proud of being held safe in the palm of a magnificent mountain where I was so small."
Outdoor skills/ competence	Participant speaks about outdoor skills and/or competence as it relates to experience/feelings/ events in the outdoors/wilderness	"you knew how dangerous it was, but you could – we were being taught how to handle it and how to live out there and how to be careful. And so it's like you knew you could survive out there and that felt really good."
Environmental understandings	Description of increased understandings of ecosystem interconnectedness, climate change processes or repercussions, or human impact on environment or ecosystem	"I think about how my actions impact the earth and having discussions about climate change on the glacier and the impact humans have on the planet awoke that thought in my brain." "Usually, when I think about glaciers, I think of only snow and ice. But I also got to see rocks and how rocks and geology impacts the ice, and melting, and rivers, and water systems."

Next, author Young also applied these same codes to participants' written responses to the open-ended survey text box questions gathered immediately and one year after the program. These data are complementary to the interview questions. Early memo-taking revealed little difference between time periods (i.e. immediately post-program versus one year later) in terms of content and themes, though some responses one year after the program show more sophisticated language. This is not unexpected, given that the passage of time allowed participants to reflect on their experience, and perhaps to develop a more polished narrative. We label all one year post-program quotations accordingly in the Findings and Discussion sections below. Nonetheless, given the similarity in content, we analyze these data together with the survey responses collected immediately after the program, as well as the interview responses.

Finally, we look for emergent themes within and across codes, and group them as they pertain to different aspects of environmental identity development.

4.6 Findings and discussion

The aspects of environmental identity development related to experiencing a glacier landscape that were most frequently highlighted by participants include relatedness and pro-environmental motivation. These are two key elements of the *Clayton* [2003] environmental identity model, and serve as the overarching dimensions under which we describe the emergent themes of our analysis. However, we note that given the integrated nature of Clayton's vision of environmental identity, there is significant overlap across dimensions, such that some themes are best described as cross-cutting. We discuss the significance of this overlap below.

4.6.1 Relatedness to nature

In Clayton's characterization, developing relatedness to the environment is a way of gaining further clarity on how one fits in the larger picture. In the context of *Girls on*

Ice, participants describe feeling both smaller as a result of the experience (e.g. "this trip made me realize how small humans are, and it was a visceral reminder that we are part of something much bigger, and so powerful"), while still sensing the sizeable influence of their position (e.g. "I guess it, kinda going back to that bigger picture, you almost don't realize how much of an impact you have, just one person. So being in the program, it really opens your eyes to a broader spectrum"). One participant explained, "before *Girls on Ice*, I didn't have any experience or a connection to the glacier ecosystem. I just thought they were high on the mountains, like, they didn't have any effect on me." After the program, several participants described feeling more "in tune" with the natural environment, and one participant relayed, "I feel more connected to all kinds of different landscapes, like, from glaciers to oceans to rivers and deserts."

Clayton [2003] also suggests that relatedness to the natural world can occur as more of a spiritual discovery, or sense of feeling unified with Mother Earth or Gaia. In describing their experiences, several participants indeed chose language that personified the landscape in such a way. One participant thought of the land "as a person," while another stated, "I feel like it's important to take care of the Earth because in the end she's taking care of us... And I think we should learn how to be more nurturing like she is." Still another participant referred to the glacier as "strong" and "confident," and a different participant poetically shared, "I was proud of being held safe in the palm of a magnificent mountain where I was so small."

Relatedness builds when ecosystem linkages are brought to light In addition to bigger-picture or spiritual relations, we observed that having an increased understanding of ecosystem interconnectedness played a strong role in building participants' relatedness to the glacier environment. During the program, instructors helped elucidate different processes, patterns, and connections in the ecosystem that may have otherwise gone unnoticed (for example, pointing out how terrestrial plant and wildlife species are distributed relative to the glacier, or explaining how glacial meltwater routes to downstream rivers and the ocean). Participants reported, "you realize how intricate and connected the environment is to everything around you," and "I guess it's a bigger spectrum, a bigger picture, definitely. Even [an instructor] talking about how the water runs to all the oceans from that one spot, it makes you notice how something so small could still have a big difference. And you read about it in textbooks and whatnot, but it's not the same as actually seeing it and actually understanding that bigger picture."

In recent years, studies have begun to suggest that successful educational interventions for climate change engagement should focus less on gains in an individual's knowledge and more on designing program elements that, among other features, demonstrate interconnectedness, as this is more likely to result in people taking active steps to respond to climate change than simple knowledge acquisition [*Allen and Crowley*, 2017]. Indeed, other research on climate change education in secondary schools promotes the importance of teaching about climate change as a system, based on the idea that bringing to light the connections between elements helps to better demonstrate impacts, and elucidates how humans both a) contribute to climate change, and b) experience the consequences [*Shepardson et al.*, 2012]. Our findings are consistent with this, demonstrating that bringing ecosystem linkages to the fore helps to build relatedness to the natural environment and, in turn, drives pro-environmental motivation.

4.6.2 Pro-environmental motivation

Immediately after the *Girls on Ice* program, all participants reported feeling inspired to undertake new activities to help the environment. When asked one year later "have you been doing any new activities to help protect/conserve the environment (e.g. recycling, school environmental club, etc.)?", almost all participants mentioned such general environmental stewardship activities as: recycling, limiting their personal emissions footprint (e.g. walking/biking/taking transit instead of driving), reducing water consumption, and sharing knowledge with others. (While recycling may have been a common response due to its inclusion in the question, it is also frequently associated with pro-environmental behavior and may even act as a gateway to other behaviors [*Berger*, 1997]). While personal, private actions such as reducing waste were more common, we note that some participants also reported having begun such activities as working at a wildlife preserve and initiating an environmental club at school. This willingness to engage in public actions differs from a study on younger 13 to 15 year-old youth identified by their teachers as 'environmental enthusiasts,' in which the authors found that navigating the complexities of early teenage years drew the study participants more to small-scale personal actions with no social risk [*Eames et al.*, 2018]. Our finding that *Girls on Ice* participants had the confidence to endeavor towards public action helps confirm the hypothesis in *Eames et al.* [2018] that promoting environmental education in secondary school rather than middle school may be more productive for encouraging larger-scale, more organized pro-environmental action.

Increased understandings of ecosystem linkages are also found to drive pro-environmental motivation, again by triggering a sense of the potentially large impacts of seemingly small actions. For example:

> 'I didn't realize how glaciers and the ocean and rivers affect everything around it. So that's kinda like the ecosystem is so complicated and connected in so many ways to different parts. And so I guess that just opened my eyes to like if you – I don't know, it's like a butterfly effect, so if you pick up trash then it can lead to huge improvements in the environment in so many ways.'

Moreover, for many participants, this pro-environmental drive from increased ecosystem understandings carries over specifically to inspire actions to combat climate change. One year after the program, one participant described, "I had no idea before *Girls On Ice* how important glaciers were. Exploring the glacier landscape was very humbling. It made me realise that I also have a responsibility in the effects of climate change. And with the knowledge of how intricate the landscape and environment on Mt Baker, I felt I had a duty to protect it." Another participant reflected: "I guess I didn't realise how the environment is connected in so many ways; from ocean to even wildlife. Because of this I feel like I will feel an obligation to do as much as I can to protect the environment so that more people can experience what I got to. The conversation about climate change really opened my eyes to this."

Sharing with others and helping the environment are connected One of the most frequent sentiments expressed by participants during the post-program interviews was the desire to share the glacier landscape with other people beyond those in the program. In particular, participants mentioned wanting to share the landscape with family members, the next generation of *Girls on Ice* participants, or with other people more generally. Several participants also mentioned wanting to share what they had learned on *Girls on Ice* in order to spread knowledge and teach others. Right after the program, one participant commented, "I will do my best to spread the knowledge I've gained on the program with as many as I can," while another reflected one year later, "Studying Gulkana most definetly [sic] changed my view on climate change. Learning and seeing the impacts of human [sic] living on the glacier, created a want inside me to inform others of the disappearance of our world's magnificent features."

Paired with this was an interest in helping the environment "stay new for the next generation of *Girls on Ice* participants, and similarly in allowing more people to experience the environment "as it is, or as the participants experience it themselves, e.g. "I would protect it because I want it to make everyone feel how it made me feel, just honored to see it because it's retreating so fast." Another participant expressed, "It's made me want to do it more because if we don't start taking care of it sooner, then it won't be there for other people to experience and enjoy. Yeah. I want other people to – more *Girls on Ice* down the road to be able to have the experience that I did. They won't have that if we don't start protecting or changing our ways."

Altogether, participants' desire to share aspects of the program with others manifested as two-directional: participants wanted to educate other people for the sake of preserving the landscape, and wanted to preserve the landscape for the sake of sharing it with other people. This demonstrates that for many participants, pro-environmental motivation is consistent with the notion that an individual's environmental identity and its constituent elements are both a product and a force [*Clayton*, 2003], given that pro-environmental motivation here is the product of participants' connection with other people, as well as a force that compels their inclusion.

4.6.3 Cross-cutting themes

We observed in this study that text that informed 'Relatedness' was also frequently coded under 'Protecting the environment,' suggesting that these two elements of Clayton's (2003) environmental identity model were highly integrated. We propose that given the setting and context of the program in a climate change-impacted glacier landscape, many participants experience a deepened sense of their position within the natural world in tandem with a call to environmental action. We explore this in the two themes to follow.

"Humanity can either hurt or help nature" Based on their interactions with the glacier landscape, many participants reported having a deepened understanding of how humans, including themselves, have an impact on the environment. One participant explained a year after the program, "Studying Gulkana most definetly [sic] changed my view on climate change. Learning and seeing the impacts of human [sic] living on the glacier, created a want inside me to inform others of the disappearance of our world's magnificent features." Another summarized more generally, "Every place that we encounter has, it [sic] affected by us. So it's important to make sure that our effect is only a positive one and that we continue to protect these places." Here we see that this strengthened sense of relatedness to the natural world due to better understanding human influence was nearly inseparable from a desire to behave pro-environmentally; these aspects of environmental identity were mentioned in tandem.

A few participants observed that the relationship between humans and environment is bidirectional. One participant noted simply, “The world needs us and we need it.” A year later, another participant also described how humans’ influence on the environment can take two forms: “It made me realize that humanity can either hurt or help nature.” Indeed, discussion of humans’ negative influence was frequent; different participants stated: “we use a lot of the environment’s resources,” “I was able to see that humans have a catastrophic impact on the rest of the earth,” and “we just are kinda ruining the planet.” Despite these strong negative impressions, participants reported their own desire to have a positive impact on the natural world. One year later, one participant offered, “I can’t bare [sic] to think that I can hurt it; therefore, I make sure I don’t and proactively work towards helping the enviro [sic],” while another said of the experience, “Yes, made me realize climate change is happening and we are the only ones who can take measures to prevent it.”

Participants mentioned several ways in which they learned through practice how their actions impacted the environment. Reflecting on their behaviors, one participant recalled,

> ‘It was little things we could do. Most people would pick up trash. I would like to think everyone. But we would go further than that. We would pick up every single tiny little crumb that we called micro trash. And so if you dropped one grain of rice, you pick it up and you eat it. So that just made you think, like we have this idea that everything is just out of sight, out of mind, you know, and that’s not true. And so this program really helped me realize the effects of just everything we do.’

Another participant observed,

> ‘Like to come from a suburban place where it’s so like centered around humans and how humans function and like works to serve humans. And then to go

> somewhere where it's like no, you have to do these things because that's what's best for the environment I think was refreshing and to some extent challenging."

We suggest that the *Girls on Ice* program design elements of discussing ecosystem interconnectedness and modeling strict leave-no-trace behavior served to provide a small/local scale example of pro-environmental behavior that helped solidify the concept of human impact on the environment. Together with an increased sense of personal relatedness to the environment, these concepts act inextricably as strong motivators for behaving in an environmentally responsible way.

Witnessing the scale of glacier loss made climate change more 'real'; inspired pro-environmental motivation The experience of interacting with the glacier proved an especially powerful aspect of the *Girls on Ice* program for participants. Many characterized the glacier as "beautiful," "magical," and "inspiring," and called interacting with it "unforgettable" and "once-in-a-lifetime." Several participants reported that experiencing the sense of scale was particularly impactful. One participant reflected, "it looks big from the camp, but then you get on the glacier and you actually start walking around it, and it's like, oh my gosh, this is so huge. I didn't expect it to be as big as it was until I actually set foot on it. And it was like, wow, this is a big one." Participants also expressed surprise over the rate of loss of glacier ice over time. One participant stated, "And I just thought, I was like, oh my gosh, how could this happen so fast?" Grasping this rate of change brought up anxiety for several participants, one of whom described, "standing where the terminus [the tongue of the glacier] was, like, decades before, and standing where it is now, and even seeing pictures from 1912 to versus now, it's been really scary."

We propose that the impact of the size and rate of ice loss is consistent with findings from research in museum settings. In exploring the characteristics that make museum artifacts especially powerful for visitors, *Leinhardt and Crowley* [2002] found that one of the most important features is simply a noteworthy sense of scale (e.g. very large) and/or a size that is different than the observer anticipated (e.g. larger than expected). Although the setting is different, the experience of being dwarfed by an immense and rapidly changing landscape feature – and again, one that has been made legendary by the media [*Leiserowitz*, 2005; *Carey*, 2007; *Doyle*, 2009] – carries the same potential for significant impact.

For many participants, seeing for themselves this surprising rate of glacier change deepened their relatedness to the environment, and particularly to the changes taking place. One participant mentioned, “To look at these ideas and concepts in a scientific way, explaining all the change that has occurred within the last few years. I don’t know. It just really makes it specific and you really see it and you really worry about climate change in that specific place.” Another participant noted a year after the program, “I know that climate change is real, and I have experienced the effects of it at home but seeing the effects of the receding glacier made it real in a different way.” These sentiments suggest that being in an environment that shows clear and visible signs of rapid climate change made the concept more real and relatable.

The understanding that the experience and landscape are under threat of ongoing change led many participants to express feeling “worried,” “scared,” and “sorrowful.” Yet despite this anxiety, most participants nonetheless report being inspired to act pro-environmentally. Participants used a number of terms to describe this motivation, including wanting to “protect,” “preserve,” “save,” “keep healthy,” “help,” “nurture,” “love,” and “care for” the natural world. Even more than simply feeling driven to behave pro-environmentally, some reported feeling obligated. Individual participants referred to caring for the environment as a “responsibility,” and a “duty.” A year after the program, one participant reflected, “The glacier is rapidly changing because of climate change and it is my generation’s task to help slow it down or reverse it, while another noted, “I have never had such a feeling of comfort in the snow before Gulkana Glacier. Being surrounded by beauty made me realize how if we dont stand up for our environment we are going to be ruining the places that bring us comfort and joy.”

For several participants, protecting the glacier environment meant keeping it the same from the moment in time of their experience, with one participant worrying that their "children will probably see the landscape as something completely different than [she] was viewing in the moment," while another stated, "it seems devastating that it would ever not be the same." A study by *Carey* [2007] is critical of this tendency to want to "re-set the clock," suggesting that one of the problematic outcomes of the "endangered glacier" narrative in common media is that it promotes an "ahistorical, paradoxical outcome by seeking to make glaciers static" when, as geologically active features, they are not. However, although glaciers are indeed always dynamic and changing due to seasonal cycles and natural variability, the long-term trend of retreat and thinning (i.e. volume change) is indeed attributable to climate change. Although it may miss some of the subtleties of ecosystem dynamics, it can be argued that participants' desire to see the glacier stay the same is generally compatible with a desire to see a climate in equilibrium.

Another critique of employing glaciers in climate change messaging and media hypothesizes that using visuals such as repeat glacier change photographs might actually fail in the supposed purpose and instead drive disengagement, given that the images show the discouraging reality that significant negative impacts have already been borne on the landscape *Doyle* [2009]. Other research also cautions that while employing strong/shocking imagery can draw attention to the importance of the issue, it can also negatively impact active engagement by provoking fear and leaving observers feeling helpless [*O'Neill and Nicholson-Cole*, 2009]. However, while participants in *Girls on Ice* do express surprise and anxiety at the ongoing rate of ice loss, our findings suggest that the anxiety participants may feel over the state of the environment acts as motivation for action rather than despair, bolstered by an increased sense of relatedness to the landscape. This may be in part because of rich discussions during the program around different ideas for individual and collective pro-environmental action.

One further critique is found again in the examination of the "endangered glacier" narrative by *Carey* [2007]. The author details how presenting glaciers as a feature in need of saving can be precarious. He writes:

> 'while it is vital to respond quickly to global warming and glacier melting, today's glacier narrative can be problematic because it contains underlying messages about what to save, how to save it, and for whom to save it. In short, popular glacier discourse can sometimes serve to: (1) legitimize and inspire Western intervention in glaciated areas; (2) portray local residents as passive victims suffering helplessly... and construe the world's glaciers as Western playgrounds and laboratories.'

Here, the author raises important concerns connected to issues of colonialism. Altogether, we would suggest that the diversity of participants on *Girls on Ice* precludes inspiring a strictly Western intervention for saving "endangered glaciers." Moreover, although the design of *Girls on Ice* curriculum is indeed rooted in Western epistemology, given the curriculum on science practice in the field, the focus remains primarily on understanding the two-directional influence of humans on landscape change (and vice versa) and on understanding ecosystem interconnectedness, elements that are not incompatible with Pacific Northwest indigenous perspectives on the natural world [*Williams and Hunn*, 2019].

4.7 Implications

Our findings offer several key lessons for future outdoor education initiatives. First, our results are consistent with a growing body of research that correlates personal experiences and belief in the reality of climate change. A review article by *McDonald et al.* [2015] explores this research in terms of the dimensions across which individuals may feel psychologically distant from climate change impacts, whether by hypothetical distance (i.e. the likelihood of the impact occurring), geographic (spatial proximity to the impact), temporal (how soon the impact will occur), and/or social (how well connected one is to the people who will be affected). Our results suggest that in-person interactions with a glacier landscape with visible, current, and cumulative climate impacts helps to alleviate each of these distances. Indeed, studies have linked belief to personal experience with weather events perceived to be the result of climate change, including drought [*Haden et al.*, 2012], heat wave events [*Joireman et al.*, 2010], or anomalous weather [*Borick and Rabe*, 2014]. Notably, perceiving these events as unusual relies on an individual's memory of past events, and is limited by the amount of time they have spent in that locale. On this note, few studies to date have examined the benefits from personal experiences with landscapes with visible signatures of long-term change. Two known exceptions are studies by *Stapleton* [2015] on an overseas travel program for youth to visit climate change-impacted locations and people, and by *Schweizer et al.* [2013] on the engagement of tourists in climate-impacted landscapes in U.S. national parks. Both were respectively found to motivate environmental action and increase salience, in line with the current study. Our findings appear to confirm known benefits, and support additional benefits, of an in-person visit to a climate-impacted landscape.

Other research has drawn attention to some of the more challenging aspects of climate change that have to date been an obstacle for effective education on the subject. These include the facts that climate change: a) for many people is a relatively invisible phenomenon compared to other environmental problems (e.g. an oil spill); b) is a long-term problem, which means the consequences may not become fully apparent during one individual's lifetime [*Schreiner et al.*, 2005]; c) may be obscured by day-to-day weather variability, which acts to mask long-term trends [*Shepardson et al.*, 2012]. We propose that experiencing in-context a glacier landscape helps to overcome these obstacles, by serving as imposing and hard-to-ignore visual evidence that transcends variability.

4.8 Conclusions

The present study explores the ways in which experiencing first-hand a climate change-impacted glacier landscape impacts environmental identity development in youth. We find that through spending eight days living on, traveling through, learning about, and scientifically studying two glacier landscapes with visible, cumulative signs of climate change, many participants reported personal changes that can be described as environmental identity growth. Situating our analyses in the environmental identity model described by *Clayton* [2003], emergent themes from interview and open-ended survey responses revealed gains in: relatedness to the natural environment, via better understanding ecosystem interconnectedness; and pro-environmental motivation, via a desire to share the landscape with others. Moreover, understanding the potential for two-directional impacts (negative and positive) of humans on the environment and witnessing the rate of glacier ice loss encouraged in tandem a deeper sense of relatedness and a desire to act pro-environmentally. We offer that glaciers serve as a useful venue for deepening belief in the reality of climate change, by showcasing visible evidence of their accumulated demise since the onset of anthropogenic climate change. This overcomes several of the challenges that have to date been a hindrance for climate change education, including relative invisibility, obscurity among fluctuating weather patterns, and a lack of sense of scale. Interacting with a glacier also provided a personal connection to climate change impacts, whereas most research on personal connections to date have been focused on experiences of climate change-attributed weather events. We suggest that future outdoor education efforts may seek out opportunities for observers to experience glacier landscapes as a pathway to developing environmental identity, with the ultimate goal of improving citizen engagement in the climate crisis.

4.9 References

Adkins, C., and B. Simmons (2002), *Outdoor, experiential, and environmental education: Converging or diverging approaches?*, ERIC Clearinghouse on Rural Education and Small Schools, AEL.

Allen, L. B., and K. Crowley (2017), Moving beyond scientific knowledge: Leveraging participation, relevance, and interconnectedness for climate education, *International Journal of Global Warming*, *12*(3-4), 299–312.

Arnold, H. E., F. G. Cohen, and A. Warner (2009), Youth and environmental action: Perspectives of young environmental leaders on their formative influences, *The Journal of Environmental Education*, *40*(3), 27–36.

Berger, I. E. (1997), The demographics of recycling and the structure of environmental behavior, *Environment and Behavior*, *29*(4), 515–531.

Bogdan, R., and S. Biklen (2007), Research for education: An introduction to theories and methods, *New York: Pearson.*

Borick, C. P., and B. G. Rabe (2014), Weather or not? Examining the impact of meteorological conditions on public opinion regarding global warming, *Weather, Climate, and Society*, *6*(3), 413–424.

Cachelin, A., K. Paisley, and A. Blanchard (2009), Using the significant life experience framework to inform program evaluation: The Nature Conservancy's Wings & Water wetlands education program, *The Journal of Environmental Education*, *40*(2), 2–14.

Carey, M. (2007), The history of ice: How glaciers became an endangered species, *Environmental History*, *12*(3), 497–527.

Carsten Conner, L. D., S. M. Perin, and E. Pettit (2018), Tacit knowledge and girls' notions about a field science community of practice, *International Journal of Science Education, Part B*, *8*(2), 164–177.

Chawla, L. (2006), Research methods to investigate significant life experiences: Review and recommendations: Reprinted from Environmental Education Research (1998) 4 (4), pp. 383–397, *Environmental Education Research*, *12*(3-4), 359–374.

Choi, S., D. Niyogi, D. Shepardson, and U. Charusombat (2010), Do earth and environmental science textbooks promote middle and high school students' conceptual development about climate change?, *Bulletin of the American Meteorological Society*, *91*(7), 889.

Clayton, S. (2003), *Identity and the natural environment: The psychological significance of nature*, MIT Press.

Crutzen, P. J., and E. F. Stoermer (2000), Global change newsletter, *The Anthropocene*, *41*, 17–18.

Culp, R. H. (1998), Adolescent girls and outdoor recreation: A case study examining constraints and effective programming, *Journal of Leisure Research*, *30*(3), 356–379.

D'Amato, L. G., and M. E. Krasny (2011), Outdoor adventure education: Applying transformative learning theory to understanding instrumental learning and personal growth in environmental education, *The Journal of Environmental Education*, *42*(4), 237–254.

De Vries, H., M. N. Elliott, D. E. Kanouse, and S. S. Teleki (2008), Using pooled kappa to summarize interrater agreement across many items, *Field Methods*, *20*(3), 272–282.

De Young, R. (2000), New ways to promote proenvironmental behavior: Expanding and evaluating motives for environmentally responsible behavior, *Journal of Social Issues*, *56*(3), 509–526.

Doyle, J. (2009), Seeing the climate?, *Ecosee: Image, Rhetoric, Nature*, pp. 279–298.

Dyurgerov, M., and M. Meier (2000), Twentieth century climate change: Evidence from small glaciers, *Proceedings of the National Academy of Sciences of the United States of America*, *97*(4), 1406–1411.

Eames, C., M. Barker, and C. Scarff (2018), Priorities, identity and the environment: Negotiating the early teenage years, *The Journal of Environmental Education*, *49*(3), 189–206.

Fielding, K. S., and M. J. Hornsey (2016), A social identity analysis of climate change and environmental attitudes and behaviors: Insights and opportunities, *Frontiers in Psychology*, *7*, 121.

Fisher, S. R. (2016), Life trajectories of youth committing to climate activism, *Environmental Education Research*, *22*(2), 229–247.

Ford, P., et al. (1986), Outdoor education: Definition and philosophy, *Resources in Education*, *21*(8).

Haden, V. R., M. T. Niles, M. Lubell, J. Perlman, and L. E. Jackson (2012), Global and local concerns: What attitudes and beliefs motivate farmers to mitigate and adapt to climate change?, *PloS one*, *7*(12), e52,882.

Hinds, J. (2011), Woodland adventure for marginalized adolescents: Environmental attitudes, identity and competence, *Applied Environmental Education & Communication*, *10*(4), 228–237.

Hsieh, H.-F., and S. E. Shannon (2005), Three approaches to qualitative content analysis, *Qualitative Health Research*, *15*(9), 1277–1288.

Joireman, J., H. B. Truelove, and B. Duell (2010), Effect of outdoor temperature, heat primes and anchoring on belief in global warming, *Journal of Environmental Psychology*, *30*(4), 358–367.

Kolb, D. (2014), *Experiential learning: Experience as the source of learning and development*, FT press.

Leinhardt, G., and K. Crowley (2002), Objects of learning, objects of talk: Changing minds in museums, *Perspectives on object-centered learning in museums*, pp. 301–324.

Leiserowitz, A. A. (2005), American risk perceptions: Is climate change dangerous?, *Risk Analysis: An International Journal*, *25*(6), 1433–1442.

Liddicoat, K. R., and M. E. Krasny (2014), Memories as useful outcomes of residential outdoor environmental education, *The Journal of Environmental Education*, *45*(3), 178–193.

Masson-Delmotte, V., P. Zhai, H.-O. Prtner, D. Roberts, J. Skea, P. Shukla, A. Pirani, W. Moufouma-Okia, C. Pan, R. Pidcock, S. Connors, J. Matthews, Y. Chen, X. Zhou, M. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (2018), IPCC, 2018: Summary for Policymakers. In: Global Warming of 1.5C. An IPCC Special Report on the impacts of global warming of 1.5C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty, *Technical report*, World Meteorological Organization.

McDonald, R. I., H. Y. Chai, and B. R. Newell (2015), Personal experience and the 'psychological distance' of climate change: An integrative review, *Journal of Environmental Psychology*, *44*, 109–118.

McGuire, N. M. (2015), Environmental education and behavioral change: An identity-based environmental education model, *International Journal of Environmental and Science Education*, *10*(5), 695–715.

Meehan, C. R., B. L. Levy, and L. Collet-Gildard (2018), Global climate change in us high school curricula: Portrayals of the causes, consequences, and potential responses, *Science Education*, *102*(3), 498–528.

Merriam, S. B., and E. J. Tisdell (2015), *Qualitative research: A guide to design and implementation*, John Wiley & Sons.

Naess, A. (1973), The shallow and the deep, long-range ecology movement. A summary, *Inquiry*, *16*(1-4), 95–100.

Ojala, M. (2015), Climate change skepticism among adolescents, *Journal of Youth Studies*, *18*(9), 1135–1153.

O'Neill, S., and S. Nicholson-Cole (2009), "Fear won't do it" promoting positive engagement with climate change through visual and iconic representations, *Science Communication*, *30*(3), 355–379.

Roe, G. H., M. B. Baker, and F. Herla (2017), Centennial glacier retreat as categorical evidence of regional climate change, *Nature Geoscience*, *10*(2), 95.

Rosenberg, M. (1981), The self-concept: Social product and social force, *Social psychology: Sociological perspectives*, pp. 593–624.

Rubin, H. J., and I. S. Rubin (2011), *Qualitative interviewing: The art of hearing data*, Sage.

Schreiner, C., E. K. Henriksen, and P. J. Kirkeby Hansen (2005), Climate education: Empowering today's youth to meet tomorrow's challenges, *Studies in Science Education*.

Schweizer, S., S. Davis, and J. Thompson (2013), Changing the conversation about climate change: A theoretical framework for place-based climate change engagement, *Environmental Communication: A Journal of Nature and Culture*, *7*(1), 42–62.

Shepardson, D. P., D. Niyogi, A. Roychoudhury, and A. Hirsch (2012), Conceptualizing climate change in the context of a climate system: Implications for climate and environmental education, *Environmental Education Research*, *18*(3), 323–352.

Stapleton, S. R. (2015), Environmental identity development through social interactions, action, and recognition, *The Journal of Environmental Education*, *46*(2), 94–113.

Stapp, W. (1969), The concept of environmental education, *Environmental Education*, *1*(1), 30–31.

Stevenson, K. T., M. N. Peterson, H. D. Bondell, S. E. Moore, and S. J. Carrier (2014), Overcoming skepticism with education: Interacting influences of worldview and climate change knowledge on perceived climate change risk among adolescents, *Climatic change*, *126*(3-4), 293–304.

Tanner, T. (1980), Significant life experiences: A new research area in environmental education, *The Journal of Environmental Education*, *11*(4), 20–24.

Whittington, A., E. N. Mack, N. W. Budbill, and P. McKenney (2011), All-girls adventure programmes: What are the benefits?, *Journal of Adventure Education and Outdoor Learning*, *11*(1), 1–14.

Whittington, A., J. E. Aspelmeier, and N. W. Budbill (2016), Promoting resiliency in adolescent girls through adventure programming, *Journal of Adventure Education and Outdoor Learning*, *16*(1), 2–15.

Williams, C. C., and L. Chawla (2016), Environmental identity formation in nonformal environmental education programs, *Environmental Education Research*, *22*(7), 978–1001.

Williams, N. M., and E. S. Hunn (2019), *Resource managers: North American and Australian hunter-gatherers*, Routledge.

Chapter 5: Conclusions

With its northern latitudes, weather patterns dominated by powerful Gulf of Alaska storms, and rugged topography reaching from sea level to ∼6200 m a.s.l., Alaska and adjacent Yukon/British Columbia support one of the largest mountain glacier complexes in the world. This extensive glacier coverage also means that as climate continues to warm, Alaska is losing glacier ice at one of the highest rates of any mountain glacier system. As a crucial component of the Earth's hydrological, climatological, and ecological systems, this ice loss carries with it innumerable consequences for the environment and for people.

In this dissertation, I set out with the principal task of examining several elements of the socio-ecological system that is concerned with glacier change in recent climate change. For this purpose, I laid out a conceptual framework to uncover the linkages between different components of this system, based on the 'press-pulse' dynamics model by *Collins et al.* [2011]. I contributed three studies in three realms of what might be considered 'applied glaciology,' by investigating the implications of glacier ice loss in different hydrological, ecological, and environmental education contexts.

To generate the dataset I used for analysis in my first two studies, I applied the coupled energy balance and hydrological routing model SnowModel-HydroFlow to generate high resolution spatially distributed fields of hydrological variables in the Juneau Icefield region in Southeast Alaska for 1980 to 2016. I calibrated the model simulations to numerous data sets including: a geodetic estimate from satellite imagery; river gauge data from long-term monitoring records; snow water equivalent data from helicopter-mounted ground penetrating radar; and ground observations of snow water equivalent and melt that I collected during three years of field campaigns on the icefield, a dataset that was first published as part of this work. Model simulations were validated against an independent satellite gravimetry dataset from NASA GRACE.

In the first study, I investigated whether, for the coastal watersheds draining west from the Juneau Icefield to the ocean, trends in magnitude and/or timing in total runoff, glacier runoff, and glacier ice melt could be detected in the time series. I undertook this study in order to fill literature gaps on whether such changes could be identified in a maritime climate dominated by extreme precipitation amounts and variability. Based on reasonably strong statistical significance and a large effect size with small confidence interval, I determined that annual glacier ice melt volumes have been increasing at a rate of nearly 10% per decade. Results also suggest that glacier runoff and total runoff for the domain have been increasing, albeit at rates that are proportionally smaller (3% and 1.4% per decade) and that are less statistically robust due to increasing contributions from precipitation. These results yield two key takeaways: 1) this region has still likely not passed the period of 'peak water' associated with persistent negative mass balance, and 2) while the magnitude of total runoff entering into riverine and marine environments may not be substantially changing, the relative proportions of different freshwater sources likely are. Moreover, I found that this pattern is amplified in spring, with glacier ice melt, glacier runoff, and total runoff volumes increasing at 16%, 7%, and 3% per decade. This earlier arrival of greater volumes of glacier ice melt and glacier runoff downstream signals a shift towards a hydrograph more closely resembling those of snowmelt-dominated basins. Finally, I found that the maximum glacier ice melt peak daily flow rate is increasing at a rate of 10% per decade, another shift that has the potential to alter downstream conditions due to greater influxes of this freshwater source. Together, these findings show that this region is undergoing a hydrological regime change, whereby the most substantial changes are to the timing and biogeochemistry of freshwater delivered downstream.

For the second study, which again leveraged model results from SnowModel-HydroFlow, I focused more closely on outflow from the Mendenhall Glacier drainage originating in the Juneau Icefield in order to examine correlations to oceanographic conditions at the nearby Auke Bay monitoring site, using both datasets as representative of broader, regional patterns. This study served to directly link terrestrial hydrological processes in glacierized terrain to downstream conditions in the nearshore marine environment, and was among the first to do so using a distributed, high temporal resolution glacio-hydrological model. I found that salinity and density in the upper 10 to 15 m of the ocean water column in May through September display substantially lower values (i.e. ~5 to 25 PSU and 2 to 15 kg m^{-3} relative to standard sea water), a likely signature of modification due to glacial freshwater input. I find that glacier runoff sampled and averaged over the seven days prior to each CTD measurement shows robust correlation to salinity and density averaged over the top 5 m. It also correlates more strongly than any other hydrological variable including total runoff, snow melt, or rain, indicating that freshwater that is sourced from or has been modified by glaciers exerts the dominant control over salinity and density in the nearshore environment. However, water temperature in the upper 10 to 15 m appears to be more strongly influenced by air temperature than by glacier runoff input, as indicated by strong positive correlations between water column and air column temperature. However, on measurement dates associated with the highest inputs of glacier runoff, temperatures in the uppermost 2 to 5 m abruptly decrease by several degrees Celsius, an indication of a dominant glacier runoff lens despite warm air temperature influences. Finally, I show evidence for decreasing trends from 1997 to 2016 in mean salinity of the upper 5 m in most months. The decrease is particularly large in August ($p = 0.01$, -3.2 PSU), which aligns with a large trend in glacier runoff amounts for August ($p = 0.02$, 15%) over the modeled period of 1980 to 2016. Overall, this study reveals that glacier runoff exerts the primary control over water column stratification within this nearshore environment, with consequences for marine organisms such as phytoplankton, crustaceans, and cold-water pelagic forage fish that occupy this portion of the water column.

The outcomes of these two studies have relevance for downstream terrestrial and aquatic ecologists and resource managers, specifically those who are charged with monitoring species populations that depend on glacier runoff for health, such as Pacific salmon. My first study increases understanding of how these populations may be under current or future stress, while the second study provides direct evidence linking terrestrial glacio-hydrological changes to changing oceanographic conditions downstream. Both enable better decision-making for managing harvest, anticipating future stressors to the aquatic ecosystem, and minimizing disruption to the environmental conditions upon which these species depend.

In the third study, I explored the impacts of experiencing first-hand these types of climate-impacted glacierized landscapes on environmental identity development in youth. In the *Girls on Ice* programs, 16-18 year-old female-identifying participants spend 8 days exploring, living on, and scientifically studying two glacier landscapes undergoing visible signs of change due to climate warming. Using qualitative methods applied to post-program interview and open-ended survey responses, I investigated how interacting with the glacier landscape and learning about climate impacts may have shifted participants' sense of connection to the natural world. I identified emerging themes rooted in conceptual foundations from an environmental identity model described by *Clayton* [2003]. I found that participants predominantly reported growth in two aspects of environmental identity: (1) relatedness, or a sense of understanding of how one fits in with the natural world; and (2) pro-environmental motivation, or a desire to act on behalf of the environment. Emergent themes revealed that those shifts occurred primarily through deepening understanding of the interconnections between elements of the ecosystem, understanding how humans impact the natural world, and experiencing in-person the scale of glacier loss. This research has implications for environmental educators and particularly those invested in shifting stances towards the belief in the reality of climate change. To date, research surrounding personal experiences with climate change has centered on extreme weather events. This study offered new insights by highlighting the potential pro-environmental impacts provided by interactions with glacier landscapes, given the imposing visual evidence of the cumulative impacts accrued since the onset of anthropogenic climate change.

Together, my research explores the varied and crucial role that glaciers serve within our environment and society, and evaluates the impacts as these glaciers continue to lose mass. The work herein has focused on decadal-scale changes to these highly dynamic glacier landscapes because of my interest in changes that are occurring rapidly and visibly, on a time scale that can be experienced over the course of a human lifetime. As I argue in my final chapter, few environments are showing such imposing visual evidence of climate change, which carry with them such fast and dramatic changes for linked ecosystems and communities downstream. In their article, *Collins et al.* [2011] proposed that the use of their conceptual socio-ecological system template for research would help to bridge the social and natural sciences, and to contribute knowledge towards helping understand and solve complex environmental challenges. I hope the work herein demonstrates the utility of this type of approach for supporting research that is diverse in perspective yet unified in overarching concern.

5.1 References

Clayton, S. (2003), *Identity and the natural environment: The psychological significance of nature*, MIT Press.

Collins, S. L., S. R. Carpenter, S. M. Swinton, D. E. Orenstein, D. L. Childers, T. L. Gragson, N. B. Grimm, J. M. Grove, S. L. Harlan, J. P. Kaye, et al. (2011), An integrated conceptual framework for long-term social–ecological research, *Frontiers in Ecology and the Environment*, *9*(6), 351–357.

Appendices

A Ch. 3 Supplementary analyses

Analysis of the role of percent glacier cover within the four instrumented basins of the Juneau Icefield (Mendenhall – 223 km^2, 56% glacier cover; Lemon Creek – 31 km^2, 45% glacier cover; Cowee – 111 km^2, 11% glacier over; and Montana – 36 km^2, 2% glacier cover) reveals results that differ from what we would expect. In Figures A.1 and A.2, which display in two ways the mean annual contributions from glacier ice melt in each basin relative to total runoff, we see that the greatest percent yield from glacier ice melt occurs in the Montana drainage, while contributions from Mendenhall and Lemon Creek are comparatively small. While as discussed in Chapters 2 and 3, we find that model performance in the basins with high percent glacier cover (Mendenhall and Lemon Creek) is strong, model reproduction of gauge observations in the lesser-glacierized basins (Montana and Cowee) is weaker. Reasons for these discrepancies are discussed previously. These findings were among the reasons that partitioning of the four basins is not discussed in greater detail in Chapter 3, and why we focused our analyses on partitioning in the Mendenhall drainage in particular, given its proximity to the Auke Bay monitoring site, and since model results here are especially robust.

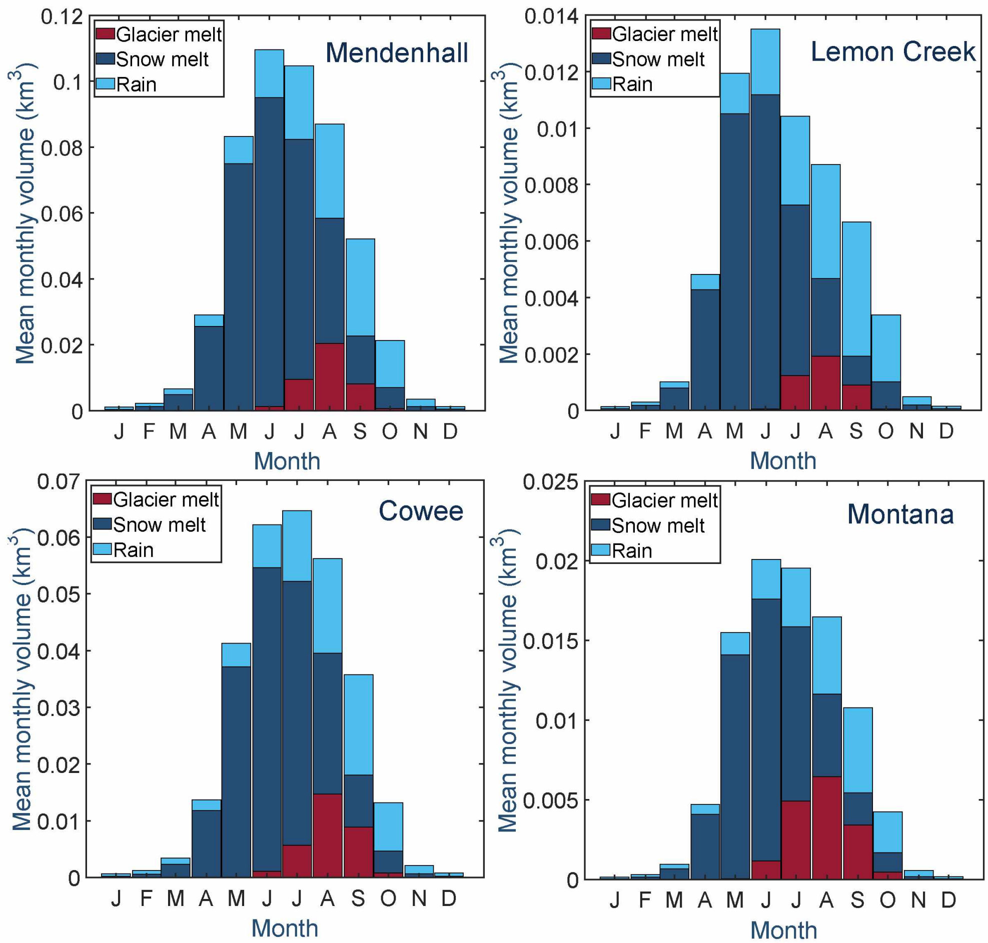

Figure A.1: Mean 1980 to 2016 monthly total runoff partitioning for the four gauged watersheds of the Juneau Icefield.

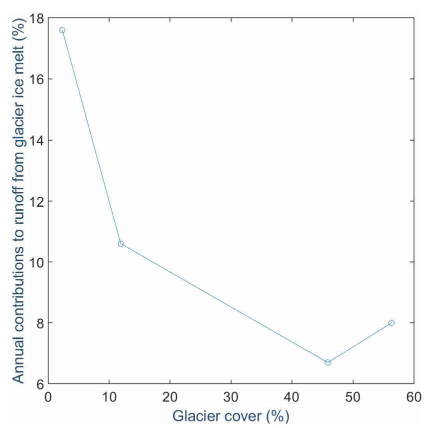

Figure A.2: Mean 1980 to 2016 modeled annual glacier ice melt as a function of percent glacier cover of the four instrumented Juneau Icefield watersheds.

B Ch. 4 Supplementary findings

During analyses for Chapter 4, it was decided to omit a discussion surrounding the role of competence, an additional element of environmental identity described in the theoretical framework from *Clayton* [2003]. Our findings and discussion related to competence were ultimately less directly related to our research question: in what ways does interacting with a climate change-impacted glacier landscape influence aspects of participants' environmental identity? That is, while other emergent themes provided insight into the role that interactions with a glacier had on environmental identity specifically as it relates to climate change, emergent themes related to competence pertained more strongly to personal and social dynamics. As they are nonetheless interesting findings related to participants' experience with the glacier landscape, I include these findings and discussion here.

B.1 Scary terrain can be overcome

Growing competence in the context of environmental identity means gaining self-sufficiency in the outdoors, whether in terms of traveling through terrain, having survival skills, and/or facing fears and challenges [*Clayton*, 2003]. One recurring theme for participants right after the program was the role of fear and anxiety caused by the 'scary' features of glacier travel. Although mountaineering instructors follow best practices in risk management such that actual risk exposure is small, glaciers harbor terrain features that require careful navigation, such as crevasses (large cracks) and steep slopes. One participant stated,

> 'I had a lot of fear, you know, for dangers, or how there's that, like, falling into a crevasse or slipping down the snow. Because the snow textures can vary a lot, and ice, walking on ice is very different. And I was always prepared – I don't know, I felt [laughs] like I always had to be ready.'

Many participants referred to glacier features as "dangerous," "intimidating," or "scary," and reported feeling "nervous" or even "fearful." However, several participants also described these scary feelings as central to building trust in the mountain guide instructors. One participant recalled one year later, "I was fearful we were going to fall in a crevasse and that as we were stepping over a crevasse it was going to widen and then we would fall in. I had to give all my faith and trust to [our mountain guide] because she knew what she was doing."

Here, participants describe feeling safe despite feeling scared, on account of being escorted through the dangerous terrain by a trusted guide. A year after the program, one participant who felt this especially strongly stated, "My comfort in a wilderness environment increases if I am with people but not if I am alone. There is something about being alone in nature that makes me terrified of nature, but since I was with a group of people for *Girls on Ice* I was more comfortable and relaxed." Interestingly, this is different than the environmental identity development pathway proposed for young children by *Green et al.* [2015], in which children need to first develop a personal sense of trust and comfort in the outdoors before they are able to progress towards gaining spatial autonomy and environmental competency. In *Girls on Ice*, participants navigate through terrain that they describe as scary, yet as the rest of our findings indicate, they experience environmental identity development nonetheless. While *Green et al.* [2015] acknowledges that the concept of autonomy on which their model is based has drawn critiques for being too independently focused for more collectivist cultures/contexts, they nonetheless propose that individual trust in nature is the foundation for environmental identity. We propose instead that trust in nature may only be achievable in certain circumstances as a shared commodity, and that this does not necessarily preclude continued individual environmental identity development. In outdoor adventure contexts, trust in the guide and/or in one's peers may be more important than trust in the natural environment. In fact, facing scary situations may actually serve as a platform for building environmental identity, by means of the sense of competence that develops as a result of overcoming one's fears. One participant captured this sentiment by reflecting, "It was a lot of fun seeing all the rivers and crevices. I mean, it was definitely dangerous and you could feel kinda the strength of the glacier. But it was a very empowering experience."

We note that this ability to rationalize in order to overcome fear is likely attributable to the older age of our study participants relative to the age group discussed in *Green et al.* [2015].

B.2 Physical challenges, skills, and team work grow empowerment

Participants additionally reported gaining confidence and empowerment from overcoming the physical challenges associated with glacier mountaineering. For some, this sense of accomplishment extended into other aspects of self-concept: "Everyday on the expedition was full of hiking and training. Exploring the glacier. I had to depend on myself in a way I hadn't before... I had to build a deeper sense of self-trust" (one year later). Several participants felt that succeeding in mountaineering pursuits on glaciers revealed other things they could achieve: "There isn't much I feel that I am not able to accomplish after climbing Mount Baker" (one year later).

Several participants also felt as though they could now handle themselves and/or manage in the outdoors, thanks to skills they had gained in this setting. One participant explained, "I think knowing skills that could save your life is – not only using them, obviously, in emergency situations, because we didn't have to, but having them with you is super empowering." Another stated, "And so it's like you knew you could survive out there and that felt really good."

Some participants also gained a sense of personal empowerment from being part of a rope team, a glacier mountaineering technique in which teammates travel as a unit and depend on one another to keep them secure in the event of a fall. Several described feeling nervous but empowered by both depending on others and being depended on themselves. One participant explained,

> 'I think there's something really empowering about being able to say like this is an action that I can do to keep myself safe. And being able to do it can keep other people safe. And I don't think I've ever felt like so like responsible for the

physical safety of others to some extent and being part of like a rope team where you're all working to make sure that every member of the team is not going to fall in the cracks. That was empowering. And I think to some extent that translates beyond like outdoor confidence to just greater confidence in myself.'

Another participant, on reaching a summit during the 'high mountain' day, described, "I felt the most powerful here because I can go anywhere and push my limits with the help of people around me."

Together, overcoming physical challenges and gaining survival skills helped to build personal competence in the outdoors, while being part of an inter-dependent team contributed to a sense of communal competence. While the former is a key element in the *Clayton* [2003] framework, communal competence is not mentioned as a possible contributor to environmental identity. We propose that competence gained as a group may be an element of environmental identity development that is unique to outdoor adventure programming (or other outdoor or environmental pursuits) where aspects of collectively gained competence could not be earned alone. While some research has examined the positive impacts of outdoor adventure programming for adolescents' general identity development [*Duerden et al.*, 2009], little research has explored the influence on environmental identity in particular. Moreover, although *Sibthorp and Jostad* [2014] has examined which social factors influence group function and outcomes during adventure programming, including what the authors term "collective efficacy" – i.e. shared belief in a group's ability to accomplish a goal together – it again has not been investigated in the context of how it may contribute to developing environmental identity. We suggest that this may be an overlooked aspect of environmental identity models, in which a sense of competence gained as a group in an interdependent setting such as during glacier mountaineering is distinct from that gained as an individual, and may provide an additional pathway towards strengthening environmental identity.

B.3 References

Clayton, S. (2003), *Identity and the natural environment: The psychological significance of nature*, MIT Press.

Duerden, M. D., M. A. Widmer, S. T. Taniguchi, and J. K. McCoy (2009), Adventures in identity development: The impact of adventure recreation on adolescent identity development, *Identity*, *9*(4), 341–359.

Green, C., D. Kalvaitis, and A. Worster (2015), Recontextualizing psychosocial development in young children: A model of environmental identity development, *Environmental Education Research*, pp. 1–24.

Sibthorp, J., and J. Jostad (2014), The social system in outdoor adventure education programs, *Journal of Experiential Education*, *37*(1), 60–74.

C Ch. 4 IRB correspondence

C.1 Modifications requested 05/06/2016

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UNIVERSITY OF ALASKA FAIRBANKS

Institutional Review Board

909 N Koyukuk Dr. Suite 212, P.O. Box 757270, Fairbanks, Alaska 99775-7270

May 6, 2016

To:	Laura Conner Principal Investigator
From:	University of Alaska Fairbanks IRB
Re:	[901319-1] Girls on Ice and climate change

Thank you for submitting the New Project referenced below. The submission was handled by Expedited Review under the requirements of 45 CFR 46.110, which identifies the categories of research eligible for expedited review.

Title:	Girls on Ice and climate change
Received:	April 28, 2016
Expedited Category:	*6 and 7*
Action:	MODIFICATIONS REQUIRED
Effective Date:	May 6, 2016
Expiration Date:	

Required Information:

Track change documents will be sent from the administrator's email with suggested changes.

This action is included on the June 8, 2016 IRB Agenda.

No changes may be made to this project without the prior review and approval of the IRB. This includes, but is not limited to, changes in research scope, research tools, consent documents, personnel, or record storage location.

C.2 Study approved 05/17/2016

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909 N Koyukuk Dr. Suite 212, P.O. Box 757270, Fairbanks, Alaska 99775-7270

May 17, 2016

To:	Laura Conner Principal Investigator
From:	University of Alaska Fairbanks IRB
Re:	[901319-2] Girls on Ice and climate change

Thank you for submitting the Revision referenced below. The submission was handled by Expedited Review under the requirements of 45 CFR 46.110, which identifies the categories of research eligible for expedited review.

Title:	Girls on Ice and climate change
Received:	May 16, 2016
Expedited Category:	7
Action:	APPROVED
Effective Date:	May 17, 2016
Expiration Date:	May 17, 2017

Required Information:

The researchers have been fully responsive to the required modifications as well as some IRB suggestions. The project can be approved and we wish them well with their important work.

This action is included on the June 8, 2016 IRB Agenda.

No changes may be made to this project without the prior review and approval of the IRB. This includes, but is not limited to, changes in research scope, research tools, consent documents, personnel, or record storage location.

C.3 Modifications accepted 06/08/2016

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909 N Koyukuk Dr. Suite 212, P.O. Box 757270, Fairbanks, Alaska 99775-7270

June 8, 2016

To:	Laura Conner Principal Investigator
From:	University of Alaska Fairbanks IRB
Re:	[901319-3] Girls on Ice and climate change

Thank you for submitting the Amendment/Modification to the survey questions referenced below. The submission was handled by Expedited Review under the requirements of 45 CFR 46.110, which identifies the categories of research eligible for expedited review.

Title:	Girls on Ice and climate change
Received:	June 1, 2016
Expedited Category:	7
Action:	APPROVED
Effective Date:	June 8, 2016
Expiration Date:	May 17, 2017

This action is included on the June 8, 2016 IRB Agenda.

No changes may be made to this project without the prior review and approval of the IRB. This includes, but is not limited to, changes in research scope, research tools, consent documents, personnel, or record storage location.

C.4 Extension approved 05/11/2017

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May 11, 2017

To:	Laura Conner Principal Investigator
From:	University of Alaska Fairbanks IRB
Re:	[901319-4] Girls on Ice and climate change

Thank you for submitting the Continuing Review/Progress Report referenced below. The submission was handled by Expedited Review under the requirements of 45 CFR 46.110, which identifies the categories of research eligible for expedited review.

Title:	Girls on Ice and climate change
Received:	May 9, 2017
Expedited Category:	7
Action:	APPROVED
Effective Date:	May 11, 2017
Expiration Date:	May 17, 2018

This action is included on the June 7, 2017 IRB Agenda.

No changes may be made to this project without the prior review and approval of the IRB. This includes, but is not limited to, changes in research scope, research tools, consent documents, personnel, or record storage location.

C.5 Extension approved 05/17/2018

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May 17, 2018

To:	Laura Conner Principal Investigator
From:	University of Alaska Fairbanks IRB
Re:	[901319-5] Girls on Ice and climate change

Thank you for submitting the Continuing Review/Progress Report referenced below. The submission was handled by Expedited Review under the requirements of 45 CFR 46.110, which identifies the categories of research eligible for expedited review.

Title:	Girls on Ice and climate change
Received:	May 14, 2018
Expedited Category:	7
Action:	APPROVED
Effective Date:	May 17, 2018
Expiration Date:	May 17, 2019

This action is included on the May 30, 2018 IRB Agenda.

No changes may be made to this project without the prior review and approval of the IRB. This includes, but is not limited to, changes in research scope, research tools, consent documents, personnel, or record storage location.

C.6 Extension approved 03/19/2019

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March 19, 2019

To:	Laura Conner Principal Investigator
From:	University of Alaska Fairbanks IRB
Re:	[901319-6] Girls on Ice and climate change

Thank you for submitting the Continuing Review/Progress Report referenced below. The submission was handled by Expedited Review under the requirements of 45 CFR 46.110, which identifies the categories of research eligible for expedited review.

Title:	Girls on Ice and climate change
Received:	March 18, 2019
Expedited Category:	7
Action:	APPROVED
Effective Date:	March 19, 2019
Expiration Date:	May 17, 2020

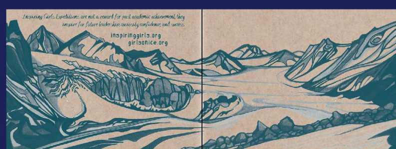
This action is included on the April 3, 2019 IRB Agenda.

No changes may be made to this project without the prior review and approval of the IRB. This includes, but is not limited to, changes in research scope, research tools, consent documents, personnel, or record storage location.

D Ch. 4 Data collection tools

D.1 Pre-program survey

Girls on Ice - Pre-program survey - Your thoughts on nature, science, and yourself



Thank you for your interest in the optional research part of Girls on Ice!

Thank you for your interest in the optional research part of Girls on Ice. As mentioned in the letter regarding your acceptance into the program, we have a survey we would like you to participate in. Your answers are confidential and will appear as anonymous. Only the Girls on Ice research team will have access to any personal information. **Please fill this survey out by Wednesday, June 15th** . The survey should take about 20 minutes. The survey is important for ensuring that you and future participants get the most out of Girls on Ice.

If you have any questions or concerns, please do not hesitate to contact us:

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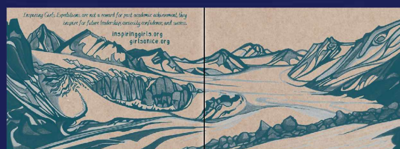
1

Girls on Ice - Pre-program survey - Your thoughts on nature, science, and yourself



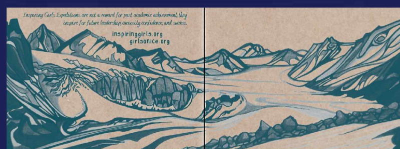
Your interest in Girls on Ice

What about Girls on Ice is most exciting to you?

Who or what inspired you to be interested in the program?

2

Girls on Ice - Pre-program survey - Your thoughts on nature, science, and yourself



Your outdoor activities

What types of outdoor/wilderness experiences and opportunities, if any, have you had in the past? Please list them here:

[ ]

Most of the time I spend outside in nature is for:

- ◯ Recreating and having fun
- ◯ Work
- ◯ Hunting/gathering/fishing
- ◯ Gardening/farming
- ◯ Other (please specify)

  [ ]

Do you do any activities to help protect/conserve the environment (e.g. recycling, school environmental club, etc.)? If so, please list them here:

[ ]

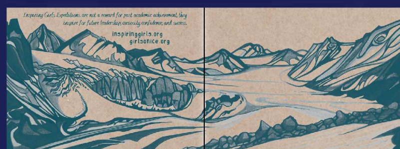
For the following questions, indicate how strongly you agree or disagree with each of the statements according to the scale:

	Strongly agree	Agree	Somewhat agree	Neutral (neither agree nor disagree)	Somewhat disagree	Disagree	Strongly disagree
Living near nature is important to me.	◯	◯	◯	◯	◯	◯	◯
I take notice of wildlife and nature wherever I am.	◯	◯	◯	◯	◯	◯	◯
Even in the middle of a city, I notice nature around me.	◯	◯	◯	◯	◯	◯	◯
I always think about how my actions affect the environment.	◯	◯	◯	◯	◯	◯	◯
I am very aware of environmental issues.	◯	◯	◯	◯	◯	◯	◯
My relationship to nature is an important part of who I am.	◯	◯	◯	◯	◯	◯	◯
I am not separate from nature, but a part of nature.	◯	◯	◯	◯	◯	◯	◯
My ideal vacation spot would be a remote, wilderness area.	◯	◯	◯	◯	◯	◯	◯
My connection to nature and the environment is a part of my spirituality.	◯	◯	◯	◯	◯	◯	◯
I feel very connected to all living things and the earth.	◯	◯	◯	◯	◯	◯	◯
I think of myself as a person who wants to protect the environment.	◯	◯	◯	◯	◯	◯	◯

Were any of the questions on this page hard to answer? If so, please describe what was challenging, and feel free to explain why you chose your answer(s):

5

Girls on Ice - Pre-program survey - Your thoughts on nature, science, and yourself



Your thoughts on nature (2)

For the following questions, indicate how strongly you agree or disagree with each of the statements according to the scale:

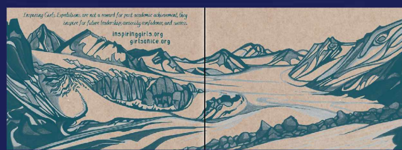
	Strongly agree	Agree	Somewhat agree	Neutral (neither agree nor disagree)	Somewhat disagree	Disagree	Strongly disagree
I spend a lot of time outdoors in nature.	◯	◯	◯	◯	◯	◯	◯
I really enjoy being in nature.	◯	◯	◯	◯	◯	◯	◯
I often learn new things about nature when I am doing outdoor activities.	◯	◯	◯	◯	◯	◯	◯
I feel confident in my ability to help protect the planet.	◯	◯	◯	◯	◯	◯	◯
The more I learn about nature, the more I want to behave responsibly towards the earth.	◯	◯	◯	◯	◯	◯	◯
I am capable of making a positive impact on the environment.	◯	◯	◯	◯	◯	◯	◯
I am able to help take care of nature.	◯	◯	◯	◯	◯	◯	◯
I believe I can contribute to solutions to environmental problems by my actions.	◯	◯	◯	◯	◯	◯	◯
Compared to other people, I believe I can make a positive impact on the environment.	◯	◯	◯	◯	◯	◯	◯

6

	Strongly agree	Agree	Somewhat agree	Neutral (neither agree nor disagree)	Somewhat disagree	Disagree	Strongly disagree
I don't think I can make any difference in solving environmental problems.	◯	◯	◯	◯	◯	◯	◯
I believe that I personally, working with others, can help solve environmental issues.	◯	◯	◯	◯	◯	◯	◯
It's hard for me to imagine myself helping to protect the planet.	◯	◯	◯	◯	◯	◯	◯

Were any of the questions on this page hard to answer? If so, please describe what was challenging, and feel free to explain why you chose your answer(s):

Girls on Ice - Pre-program survey - Your thoughts on nature, science, and yourself



Your thoughts on science

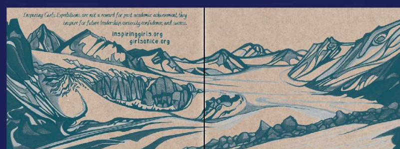
For the following questions, indicate how strongly you agree or disagree with each of the statements according to the scale:

	Strongly agree	Agree	Somewhat agree	Neutral (neither agree nor disagree)	Somewhat disagree	Disagree	Strongly disagree
Scientists use imagination and creativity in their work.	○	○	○	○	○	○	○
Science and art do not have much in common with each other.	○	○	○	○	○	○	○
Scientists' observations of the same event will be the same because scientists are objective.	○	○	○	○	○	○	○
Scientists' personalities affect the way they observe the world.	○	○	○	○	○	○	○
Scientists' observations of the same event will be the same because observations are facts.	○	○	○	○	○	○	○
Scientific research is not influenced by ethnicity or cultural background because scientists are trained to conduct "pure," unbiased studies.	○	○	○	○	○	○	○

	Strongly agree	Agree	Somewhat agree	Neutral (neither agree nor disagree)	Somewhat disagree	Disagree	Strongly disagree
All cultures conduct scientific research the same way because science is universal and independent of society and culture.	○	○	○	○	○	○	○
Scientists use different types of methods to conduct scientific investigations.	○	○	○	○	○	○	○
When scientists use the scientific method correctly, their results are true and accurate.	○	○	○	○	○	○	○
Scientific knowledge is durable, that is, stable over time.	○	○	○	○	○	○	○
Scientists use intuition in interpreting their observations.	○	○	○	○	○	○	○
Scientific knowledge is certain or exact.	○	○	○	○	○	○	○
Scientific knowledge is a part of social and cultural traditions.	○	○	○	○	○	○	○

Were any of the questions on this page hard to answer? If so, please describe what was challenging, and feel free to explain why you chose your answer(s):

Girls on Ice - Pre-program survey - Your thoughts on nature, science, and yourself



Your thoughts on humans in nature

For the following questions, indicate how strongly you agree or disagree with each of the statements according to the scale:

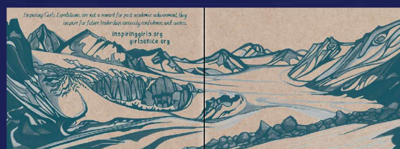
	Strongly agree	Agree	Somewhat agree	Neutral (neither agree nor disagree)	Somewhat disagree	Disagree	Strongly disagree
We are approaching the limit of the number of people the earth can support.	○	○	○	○	○	○	○
The balance of nature is very delicate and easily upset.	○	○	○	○	○	○	○
Humans have the right to modify the natural environment to suit their needs.	○	○	○	○	○	○	○
Humankind was created to rule over the rest of nature.	○	○	○	○	○	○	○
When humans interfere with nature it often produces disastrous consequences.	○	○	○	○	○	○	○
Plants and animals exist primarily to be used by humans.	○	○	○	○	○	○	○
Humans must live in harmony with the rest of nature in order to survive.	○	○	○	○	○	○	○
The earth is like a spaceship with only limited room and resources.	○	○	○	○	○	○	○

10

Were any of the questions on this page hard to answer? If so, please describe what was challenging, and feel free to explain why you chose your answer(s):

11

Girls on Ice - Pre-program survey - Your thoughts on nature, science, and yourself



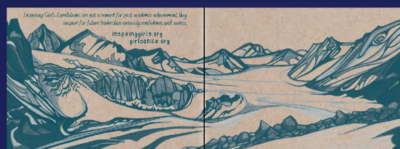
Your abilities

Please rate the following items on a scale of 1 to 10, with **1 being the lowest and 10 the highest.**

	1	2	3	4	5	6	7	8	9	10
Your intellectual abilities										
Your ability in science										
Your ability in art										
Your confidence in your physical skills										
Your comfort in a wilderness environment										
Your confidence in your outdoor skills (i.e. traveling or surviving in nature)										
Your confidence in your outdoor knowledge (i.e. understanding of ecosystems and nature)										
Your confidence in your ability to help protect the planet										
Your confidence in success in your future career										

D.2 Post-program survey

Girls on Ice - Post-program survey - Your thoughts on nature, science, and yourself



Thank you for your interest in the optional research part of Girls on Ice!

Thank you for your participation in the optional research part of Girls on Ice. As mentioned before the program, we have a survey we would like you to participate in. Your answers are confidential and will appear as anonymous. Only the Girls on Ice research team will have access to any personal information. **Please fill this survey out by Friday, July 8th.** The survey should take 15-20 minutes. This survey is important for ensuring that you and future participants get the most out of Girls on Ice.

If you have any questions or concerns, please do not hesitate to contact us:

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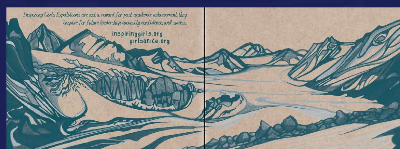
Girls on Ice - Post-program survey - Your thoughts on nature, science, and yourself



After Girls on Ice

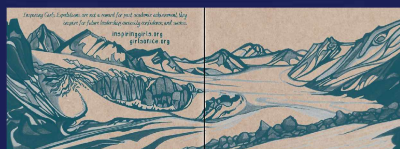
Thinking back on your Girls on Ice experience, what was the most exciting part of the trip for you?

What about your life (now or in the future) are you inspired to do differently because of Girls on Ice? What activity or event of Girls on Ice triggered that inspiration?

Did Girls on Ice change your feelings about outdoor/wilderness experiences? If yes, how so?

Are you inspired to do any new activities to help protect/conserve the environment (e.g. recycling, school environmental club, etc.)? If so, please list them here:

Girls on Ice - Post-program survey - Your thoughts on nature, science, and yourself



Your thoughts on science

For the following questions, indicate how strongly you agree or disagree with each of the statements according to the scale:

	Strongly agree	Agree	Somewhat agree	Neutral (neither agree nor disagree)	Somewhat disagree	Disagree	Strongly disagree
Scientists use imagination and creativity in their work.	◯	◯	◯	◯	◯	◯	◯
Science and art do not have much in common with each other.	◯	◯	◯	◯	◯	◯	◯
Scientists' observations of the same event will be the same because scientists are objective.	◯	◯	◯	◯	◯	◯	◯
Scientists' personalities affect the way they observe the world.	◯	◯	◯	◯	◯	◯	◯
Scientists' observations of the same event will be the same because observations are facts.	◯	◯	◯	◯	◯	◯	◯
Scientific research is not influenced by ethnicity or cultural background because scientists are trained to conduct "pure," unbiased studies.	◯	◯	◯	◯	◯	◯	◯

3

	Strongly agree	Agree	Somewhat agree	Neutral (neither agree nor disagree)	Somewhat disagree	Disagree	Strongly disagree
All cultures conduct scientific research the same way because science is universal and independent of society and culture.							
Scientists use different types of methods to conduct scientific investigations.							
When scientists use the scientific method correctly, their results are true and accurate.							
Scientific knowledge is durable, that is, stable over time.							
Scientists use intuition in interpreting their observations.							
Scientific knowledge is certain or exact.							
Scientific knowledge is a part of social and cultural traditions.							

Were any of the questions on this page hard to answer? If so, please describe what was challenging, and feel free to explain why you chose your answer(s):

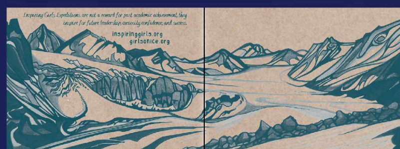
4

For the following questions, indicate how strongly you agree or disagree with each of the statements according to the scale:

	Strongly agree	Agree	Somewhat agree	Neutral (neither agree nor disagree)	Somewhat disagree	Disagree	Strongly disagree
Living near nature is important to me.							
I take notice of wildlife and nature wherever I am.							
Even in the middle of a city, I notice nature around me.							
I always think about how my actions affect the environment.							
I am very aware of environmental issues.							
My relationship to nature is an important part of who I am.							
I am not separate from nature, but a part of nature.							
My ideal vacation spot would be a remote, wilderness area.							
My connection to nature and the environment is a part of my spirituality.							
I feel very connected to all living things and the earth.							
I think of myself as a person who wants to protect the environment.							

Were any of the questions on this page hard to answer? If so, please describe what was challenging, and feel free to explain why you chose your answer(s):

Girls on Ice - Post-program survey - Your thoughts on nature, science, and yourself



Your thoughts on nature (2)

For the following questions, indicate how strongly you agree or disagree with each of the statements according to the scale:

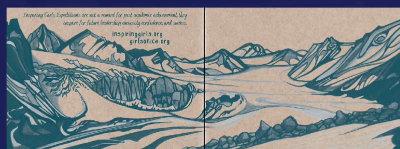
	Strongly agree	Agree	Somewhat agree	Neutral (neither agree nor disagree)	Somewhat disagree	Disagree	Strongly disagree
I spend a lot of time outdoors in nature.	○	○	○	○	○	○	○
I really enjoy being in nature.	○	○	○	○	○	○	○
I often learn new things about nature when I am doing outdoor activities.	○	○	○	○	○	○	○
I feel confident in my ability to help protect the planet.	○	○	○	○	○	○	○
The more I learn about nature, the more I want to behave responsibly towards the earth.	○	○	○	○	○	○	○
I am capable of making a positive impact on the environment.	○	○	○	○	○	○	○
I am able to help take care of nature.	○	○	○	○	○	○	○
I believe I can contribute to solutions to environmental problems by my actions.	○	○	○	○	○	○	○
Compared to other people, I believe I can make a positive impact on the environment.	○	○	○	○	○	○	○

	Strongly agree	Agree	Somewhat agree	Neutral (neither agree nor disagree)	Somewhat disagree	Disagree	Strongly disagree
I don't think I can make any difference in solving environmental problems.	◯	◯	◯	◯	◯	◯	◯
I believe that I personally, working with others, can help solve environmental issues.	◯	◯	◯	◯	◯	◯	◯
It's hard for me to imagine myself helping to protect the planet.	◯	◯	◯	◯	◯	◯	◯

Were any of the questions on this page hard to answer? If so, please describe what was challenging, and feel free to explain why you chose your answer(s):

8

Girls on Ice - Post-program survey - Your thoughts on nature, science, and yourself



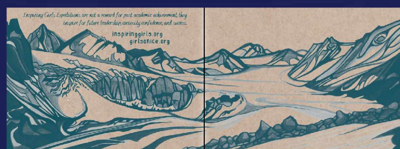
Your thoughts on humans in nature

For the following questions, indicate how strongly you agree or disagree with each of the statements according to the scale:

	Strongly agree	Agree	Somewhat agree	Neutral (neither agree nor disagree)	Somewhat disagree	Disagree	Strongly disagree
We are approaching the limit of the number of people the earth can support.	○	○	○	○	○	○	○
The balance of nature is very delicate and easily upset.	○	○	○	○	○	○	○
Humans have the right to modify the natural environment to suit their needs.	○	○	○	○	○	○	○
Humankind was created to rule over the rest of nature.	○	○	○	○	○	○	○
When humans interfere with nature it often produces disastrous consequences.	○	○	○	○	○	○	○
Plants and animals exist primarily to be used by humans.	○	○	○	○	○	○	○
Humans must live in harmony with the rest of nature in order to survive.	○	○	○	○	○	○	○
The earth is like a spaceship with only limited room and resources.	○	○	○	○	○	○	○

Were any of the questions on this page hard to answer? If so, please describe what was challenging, and feel free to explain why you chose your answer(s):

Girls on Ice - Post-program survey - Your thoughts on nature, science, and yourself



Your abilities

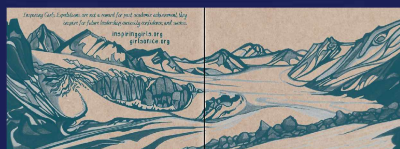
Please rate the following items on a scale of 1 to 10, with **1 being the lowest and 10 the highest.**

	1	2	3	4	5	6	7	8	9	10
Your intellectual abilities	○	○	○	○	○	○	○	○	○	○
Your ability in science	○	○	○	○	○	○	○	○	○	○
Your ability in art	○	○	○	○	○	○	○	○	○	○
Your confidence in your physical skills	○	○	○	○	○	○	○	○	○	○
Your comfort in a wilderness environment	○	○	○	○	○	○	○	○	○	○
Your confidence in success in your future career	○	○	○	○	○	○	○	○	○	○

Thinking back, how would you rate your abilities in these areas **BEFORE** you participated in Girls on Ice? Again, please rate the items on a scale of 1 to 10, with **1 being the lowest and 10 the highest.**

	1	2	3	4	5	6	7	8	9	10
Your intellectual abilities	○	○	○	○	○	○	○	○	○	○
Your ability in science	○	○	○	○	○	○	○	○	○	○
Your ability in art	○	○	○	○	○	○	○	○	○	○
Your confidence in your physical skills	○	○	○	○	○	○	○	○	○	○
Your comfort in a wilderness environment	○	○	○	○	○	○	○	○	○	○
Your confidence in your outdoor skills (i.e. traveling or surviving in nature)	○	○	○	○	○	○	○	○	○	○
Your confidence in your outdoor knowledge (i.e. understanding of ecosystems and nature)	○	○	○	○	○	○	○	○	○	○
Your confidence in your ability to help protect the planet	○	○	○	○	○	○	○	○	○	○
Your confidence in success in your future career	○	○	○	○	○	○	○	○	○	○

Girls on Ice - Post-program survey - Your thoughts on nature, science, and yourself



Your future education

Are you planning on going to college?

- ◯ Yes
- ◯ No
- ◯ Maybe (please elaborate)

Did discussions you had with instructors or other girls during Girls on Ice influence your decision on whether to attend college?

- ◯ Yes
- ◯ No

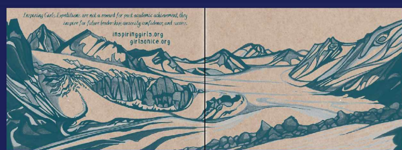
In what ways?

During high school or college, I would like to take a course in:

	Yes	No
Physics	◯	◯
Biology	◯	◯
Earth Sciences	◯	◯
Chemistry	◯	◯
Art	◯	◯
Music	◯	◯

D.3 One year later post-program survey

Girls on Ice - One year later



Thank you for your interest in the optional research part of Girls on Ice

Thank you for your participation in the optional research part of Girls on Ice. As mentioned before the program, we have a survey we would like you to participate in. Your answers are confidential and will appear as anonymous. Only the Girls on Ice research team will have access to any personal information. **Please fill this survey out by Friday, June 30th.** The survey should take 15-20 minutes. Benefits of this survey are that it will offer you a chance to reflect on your Girls on Ice experience, and will help ensure that you and future participants get the most out of Girls on Ice.

If you have any questions or concerns, please do not hesitate to contact us:

Joanna Young, M.S.
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University of Alaska Fairbanks
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Laura Conner, Ph.D.
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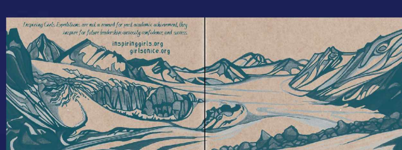
Girls on Ice - One year later



After Girls on Ice

1

What did you learn about yourself on Girls on Ice?

Have you been inspired to do anything in your life differently because of Girls on Ice? What activity or event of Girls on Ice triggered that inspiration?

If you were able to return now to the Gulkana Glacier (Alaska team) or Easton Glacier (Cascades team), what do you think you would feel? Why?

Thinking back, was there ever a moment on Girls on Ice where you felt anxious or unsure? What was it? How did you overcome it?

Girls on Ice - One year later

After Girls on Ice

2

When during Girls on Ice did you feel most powerful? Why?

Did exploring a glacier landscape change **how you understand** the environment and/or climate change? Why or why not?

Did exploring a glacier landscape change **how you feel** about the environment and/or climate change? Why or why not?

Since Girls on Ice, have you been doing any new activities to help protect/conserve the environment (e.g. recycling, school environmental club, etc.)? Please describe:

Girls on Ice - One year later

Your
abilities

Please rate the following items on a scale of 1 to 10, with **1 being the lowest and 10 the highest.**

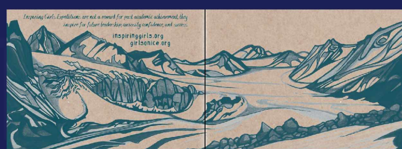
	1	2	3	4	5	6	7	8	9	10
Your comfort in a wilderness environment	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯
Your confidence in your outdoor skills (i.e. traveling or surviving in nature)	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯
Your confidence in your outdoor knowledge (i.e. understanding of ecosystems and nature)	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯
Your confidence in your ability to help protect the planet	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯

Thinking back, how would you rate your abilities in these areas **BEFORE** you participated in Girls on Ice? Again, please rate the items on a scale of 1 to 10, with **1 being the lowest and 10 the highest.**

	1	2	3	4	5	6	7	8	9	10
Your comfort in a wilderness environment	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯
Your confidence in your outdoor skills (i.e. traveling or surviving in nature)	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯
Your confidence in your outdoor knowledge (i.e. understanding of ecosystems and nature)	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯
Your confidence in your ability to help protect the planet	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯

Were any of the questions on this page hard to answer? If so, please describe what was challenging, and feel free to explain why you chose your answer(s):

Girls on Ice - One year later



Your thoughts on nature

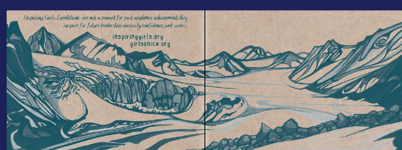
5

For the following questions, indicate how strongly you agree or disagree with each of the statements according to the scale:

	Strongly agree	Agree	Somewhat agree	Neutral (neither agree nor disagree)	Somewhat disagree	Disagree	Strongly disagree
Living near nature is important to me.	◯	◯	◯	◯	◯	◯	◯
I take notice of wildlife and nature wherever I am.	◯	◯	◯	◯	◯	◯	◯
Even in the middle of a city, I notice nature around me.	◯	◯	◯	◯	◯	◯	◯
I always think about how my actions affect the environment.	◯	◯	◯	◯	◯	◯	◯
I am very aware of environmental issues.	◯	◯	◯	◯	◯	◯	◯
My relationship to nature is an important part of who I am.	◯	◯	◯	◯	◯	◯	◯
I am not separate from nature, but a part of nature.	◯	◯	◯	◯	◯	◯	◯
My ideal vacation spot would be a remote, wilderness area.	◯	◯	◯	◯	◯	◯	◯
My connection to nature and the environment is a part of my spirituality.	◯	◯	◯	◯	◯	◯	◯
I feel very connected to all living things and the earth.	◯	◯	◯	◯	◯	◯	◯
I think of myself as a person who wants to protect the environment.	◯	◯	◯	◯	◯	◯	◯

Were any of the questions on this page hard to answer? If so, please describe what was challenging, and feel free to explain why you chose your answer(s):

Girls on Ice - One year later



Your thoughts on nature (2)

For the following questions, indicate how strongly you agree or disagree with each of the statements according to the scale:

	Strongly agree	Agree	Somewhat agree	Neutral (neither agree nor disagree)	Somewhat disagree	Disagree	Strongly disagree
I spend a lot of time outdoors in nature.	○	○	○	○	○	○	○
I really enjoy being in nature.	○	○	○	○	○	○	○
I often learn new things about nature when I am doing outdoor activities.	○	○	○	○	○	○	○
I feel confident in my ability to help protect the planet.	○	○	○	○	○	○	○
The more I learn about nature, the more I want to behave responsibly towards the earth.	○	○	○	○	○	○	○
I am capable of making a positive impact on the environment.	○	○	○	○	○	○	○
I am able to help take care of nature.	○	○	○	○	○	○	○

	Strongly agree	Agree	Somewhat agree	Neutral (neither agree nor disagree)	Somewhat disagree	Disagree	Strongly disagree
I believe I can contribute to solutions to environmental problems by my actions.	○	○	○	○	○	○	○
Compared to other people, I believe I can make a positive impact on the environment.	○	○	○	○	○	○	○
I don't think I can make any difference in solving environmental problems.	○	○	○	○	○	○	○
I believe that I personally, working with others, can help solve environmental issues.	○	○	○	○	○	○	○
It's hard for me to imagine myself helping to protect the planet.	○	○	○	○	○	○	○

Were any of the questions on this page hard to answer? If so, please describe what was challenging, and feel free to explain why you chose your answer(s):

Girls on Ice - One year later

Thank you for your time!

Thank you very much for your participation in this survey. We really appreciate it!

8

D.4 Interview question list

Interview Questions

1. What was the most memorable or exciting part of GOI? What did you learn?

2. Describe how you feel about the environment and ecosystem. Has Girls on Ice changed how you feel about the environment and ecosystem, and if so, how? How did you feel about the environment before participating in Girls on Ice?

3. How has GOI impacted the way you feel about caring for the Earth? How did you feel about caring for the Earth prior to the program?

4. What does “leadership” mean to you? How has Girls on Ice impacted your ideas about leadership? Think back to before you participated in Girls on Ice. What were your ideas about leadership then?

5. Did Girls on Ice impact your confidence in your outdoor skills, and if so, how? Think back to before you participated in Girls on Ice. What was your confidence in your outdoor skills prior to participating in the program (rate on scale of 1-10 before and after)?

6. Did Girls on Ice change what you understand about climate change? What did you learn?

7. What was it like to be on a glacier? Did living on, exploring and learning about a glacier impact how you feel about the environment and/or climate change? If so, how?

8. Do you feel that Girls on Ice will inspire you to do anything differently in your life when you are back at home? If so, what?